UTAH GEOLOGICAL SURVEY
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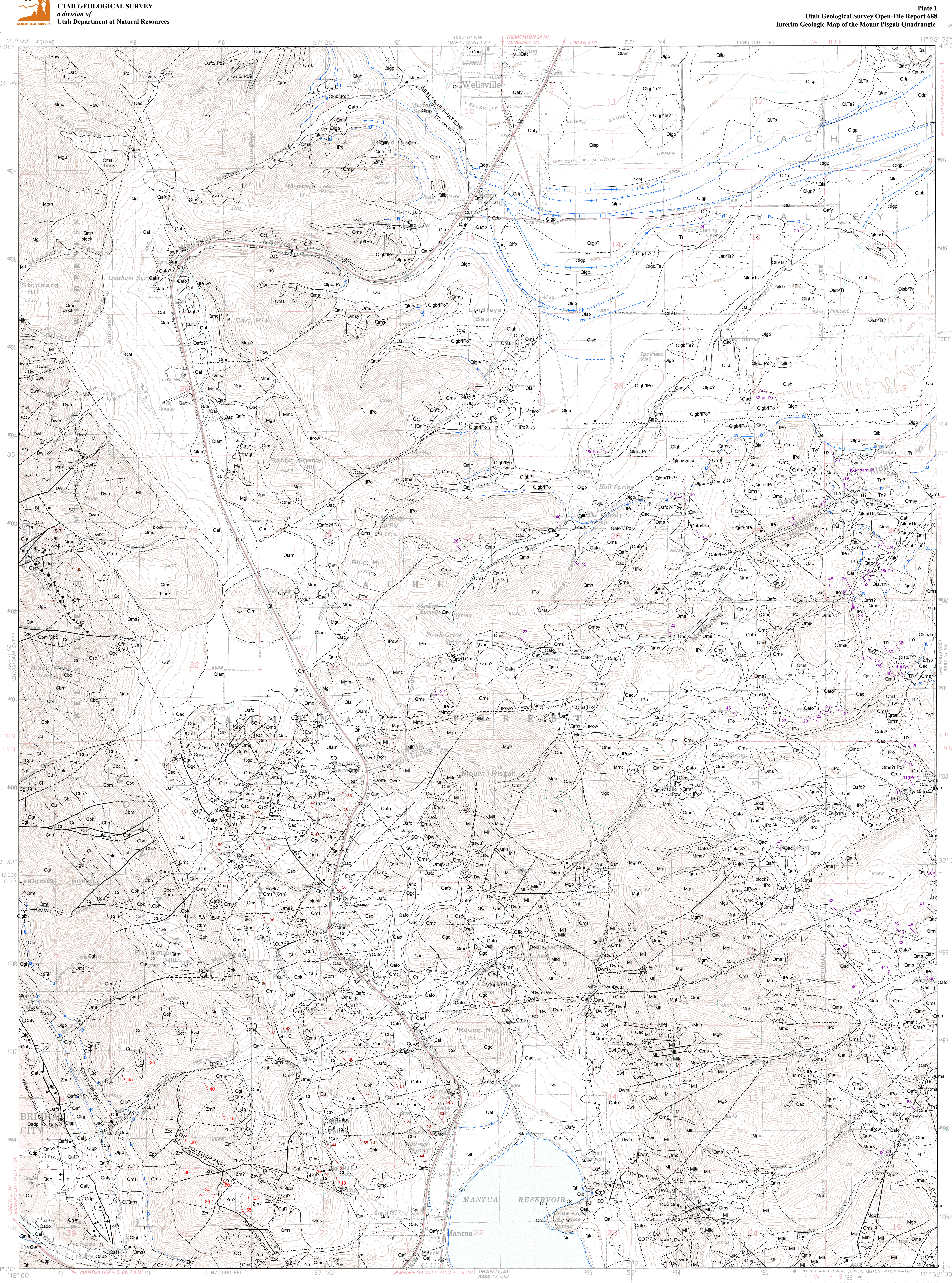

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11°30′
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 2018

SCALE 1:24,000
1 0.5 0 1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 0.5 0 1 KILOMETER
CONTOUR INTERVAL 40 FEET
SUPPLEMENTARY CONTOUR INTERVAL 20 FEET

UTAH
QUADRANGLE LOCATION

Base from USGS Mount Pisgah 7.5′ Quadrangle (1991)
Projection: UTM Zone 12
Datum: NAD 1927

Project Manager: Doug Sprinkle
Field Mapping: various

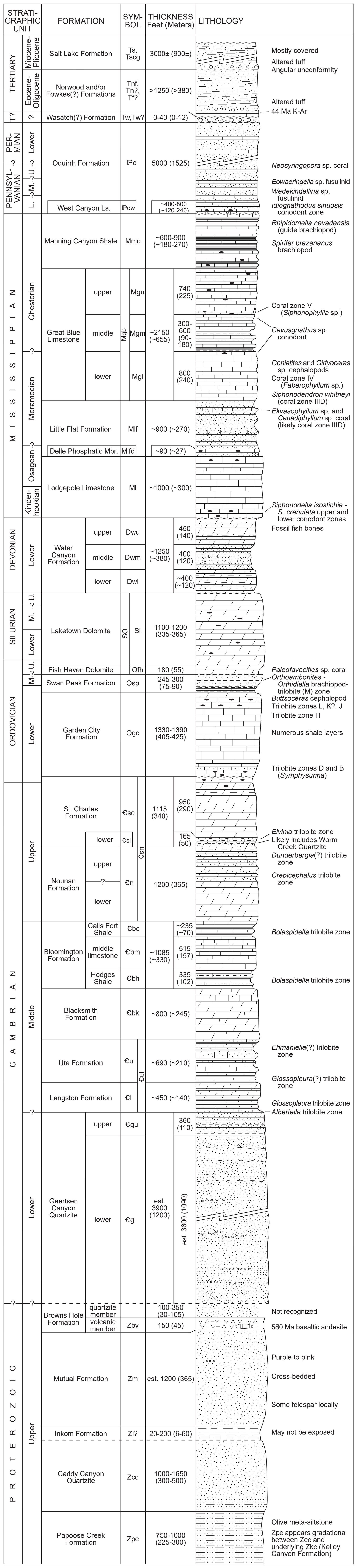
Utah Geological Survey
1594 West North Temple, Suite 3110
P.O. Box 146100, Salt Lake City, UT 84114-6100
(801) 537-3300
geology.utah.gov

INTERIM GEOLOGIC MAP OF THE MOUNT PISGAH QUADRANGLE, BOX ELDER AND CACHE COUNTIES, UTAH

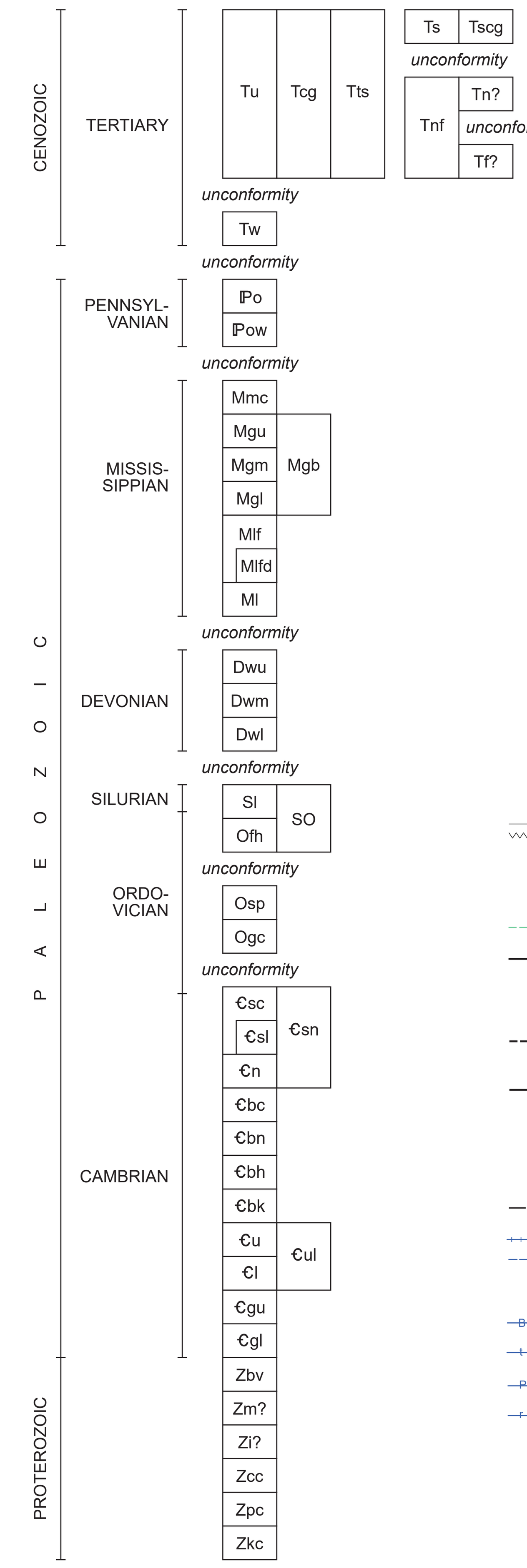
by
Jon K. King, Barry J. Solomon, and Robert Q. Oaks, Jr.

2018

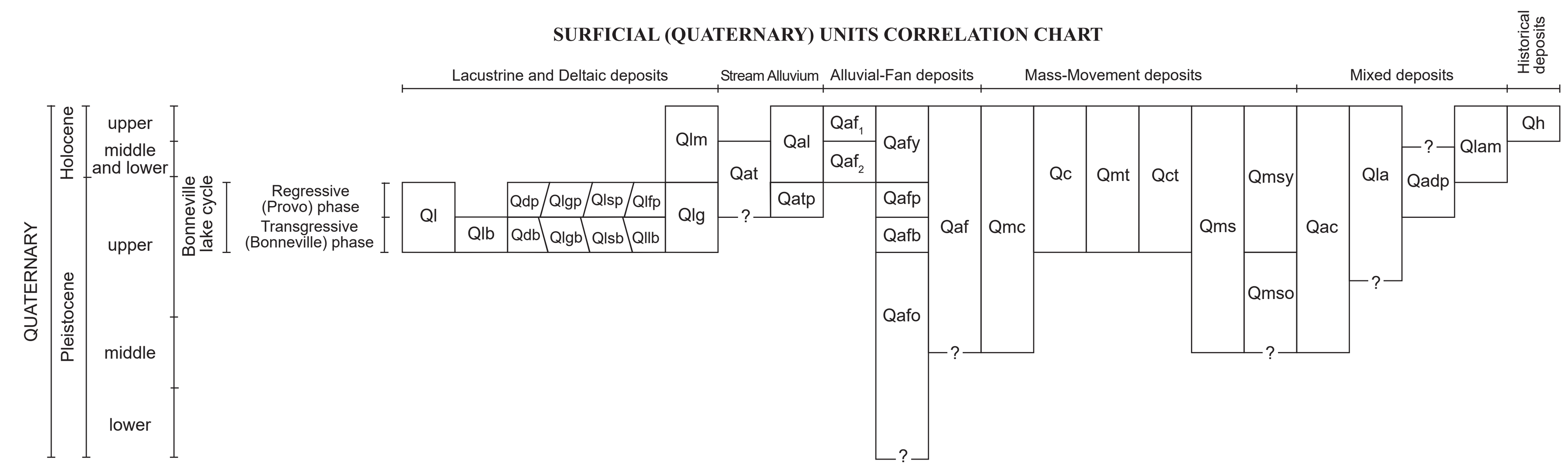
LITHOLOGIC COLUMN



BEDROCK CORRELATION CHART



SURFICIAL (QUATERNARY) UNITS CORRELATION CHART



GEOLOGIC SYMBOLS

Contact - dashed where approximately located, dotted where concealed, queried where existence uncertain or location is very poorly constrained. Sawteeth where gradational or scratch. Some contacts shown between adjacent landslides and slumps.

Marker bed

Fault, moderately to steeply dipping - dashed where approximately located, dotted where concealed, queried where existence uncertain. Bar and ball on downthrown side where offset known.

Thrust fault, filled teeth on upper plate, dashed because approximately located.

Box Elder fault, open teeth on upper plate, dashed where approximately located, dotted where concealed. Low angle to bedding and normal offset, younger strata on older (not thrust). Amount of strata "cut out" is limited, except where concealed along Wasatch fault zone.

Lineament, possible fault or contact.

Lake Bonneville shorelines - beach ridge on left; other shorelines dashed where approximately located, queried and dotted where existence and/or location uncertain.

Bonneville shoreline

unnamed transgressive shoreline

Provo shoreline

unnamed regressive shoreline

75

Strike and dip of bedding (in degrees), upright

Smith and Oaks, 1997 (purple)

Jensen and others, 1995 (brownish red)

Sorensen and Crittenden, 1976b (red)

Gelnett, 1958 (brown), upright approximate

Strike and dip of bedding, photo interpreted

Sample location, potassium-argon date (see table 1)

Mass-movement scarp

Fluvial terrace scarp

Sinkhole

Qh — Outline of gravel pit, road bed, or other human disturbance

Ql/Ts — Thin Quaternary unit over another unit, for example Ql/Ts

Qms (block) — Landslide that is nearly intact block; rock unit in parentheses if few units, for example Qms?(Csn) and Qms(₽o); queried, Qms?, where blocks may be in place.

Table 1. Potassium-argon age determinations for Norwood-Fowkes unit "tuffaceous sandstone" (sample location NW1/4NW1/4 section 30, T. 10 N., R. 1 E.)

hornblende concentrate

Argon Analyses:	^{40}*Ar, ppm	^{40}*Ar/Total ^{40}Ar	Ave. ^{40}*Ar,ppm
	.001861	0.382	
	.001787	0.510	0.001826
	.001831	0.413	

Potassium Analyses:	%K	Ave. %K	^{40}K, ppm
	0.582		
	0.596	0.589	0.703

Ratio: $\frac{^{40}*Ar}{^{40}K} = 0.002599$

Constants Used:
$\lambda_\beta = 4.962 \times 10^{-10}$/year
$(\lambda_e + \lambda'_e) = 0.581 \times 10^{-10}$/year
$^{40}K/K = 1.193 \times 10^{-4}$ g/g

Age Equation: $AGE = \frac{1}{\lambda_\beta + (\lambda_e + \lambda'_e)} \ln \left[\frac{\lambda_\beta + (\lambda_e + \lambda'_e)}{(\lambda_e + \lambda'_e)} \times \frac{^{40}*Ar}{^{40}K} + 1\right]$

Age: 44.2 ± 1.7 Ma

biotite concentrate

Argon Analyses:	^{40}*Ar, ppm	^{40}*Ar/Total ^{40}Ar	Ave. ^{40}*Ar,ppm
	.01308	0.417	
	.01291	0.406	0.01299

Potassium Analyses:	%K	Ave. %K	^{40}K, ppm
	3.844		
	3.769	3.807	4.541

Ratio: $\frac{^{40}*Ar}{^{40}K} = 0.002862$

Constants Used:
$\lambda_\beta = 4.962 \times 10^{-10}$/year
$(\lambda_e + \lambda'_e) = 0.581 \times 10^{-10}$/year
$^{40}K/K = 1.193 \times 10^{-4}$ g/g

Age Equation: $AGE = \frac{1}{\lambda_\beta + (\lambda_e + \lambda'_e)} \ln \left[\frac{\lambda_\beta + (\lambda_e + \lambda'_e)}{(\lambda_e + \lambda'_e)} \times \frac{^{40}*Ar}{^{40}K} + 1\right]$

Age: 48.6 ± 1.3 Ma

Analyses reported by Geochron Laboratories, Cambridge Massachusetts, March 17, 1995
NOTES: ^{40}*Ar = radiogenic ^{40}Ar, Ma = millions of years.

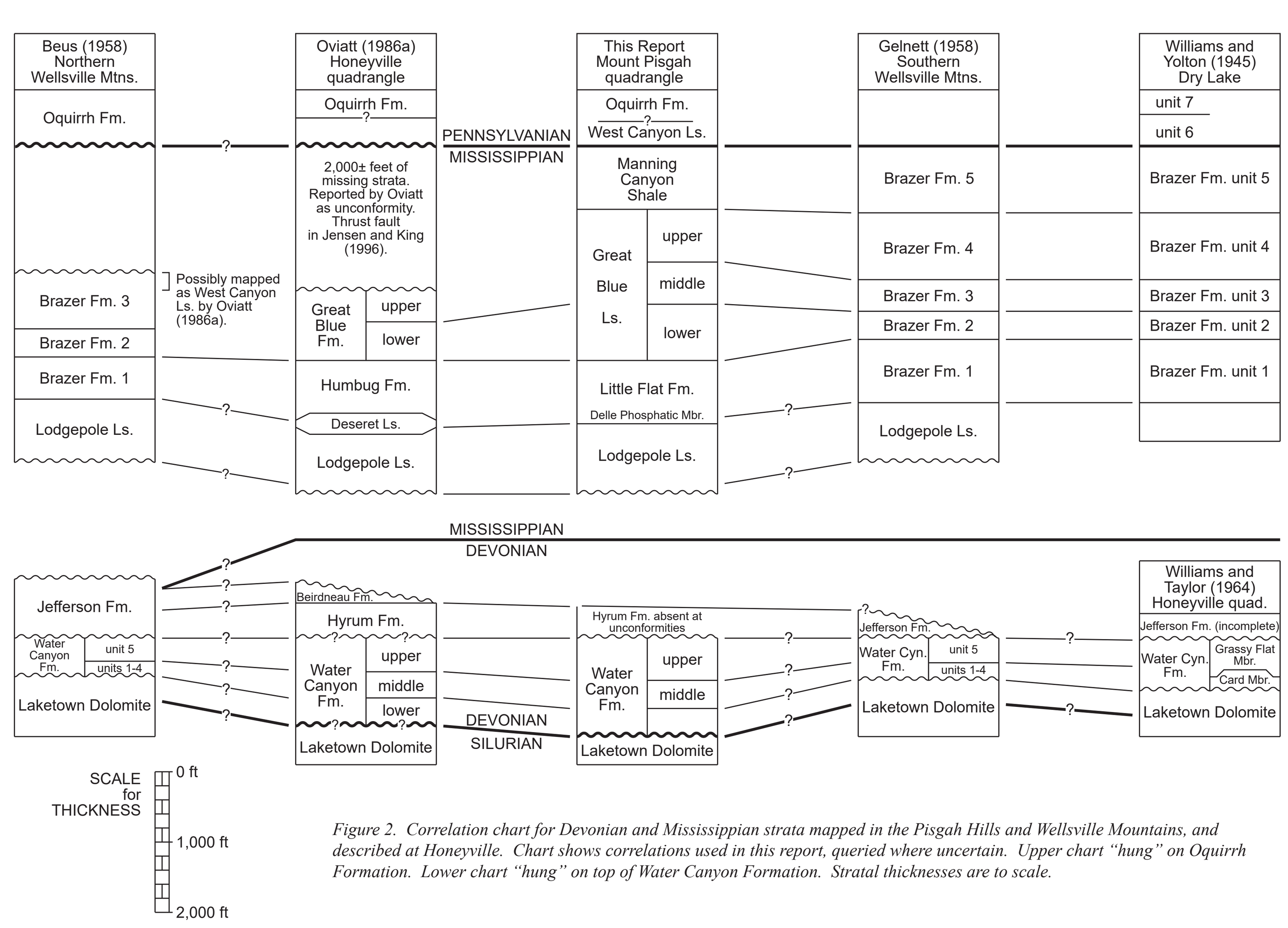


Figure 2. Correlation chart for Devonian and Mississippian strata mapped in the Pisgah Hills and Wellsville Mountains, and described at Honeyville. Chart shows correlations used in this report, queried where uncertain. Upper chart "hung" on Oquirrh Formation. Lower chart "hung" on top of Water Canyon Formation. Strata thicknesses are to scale.

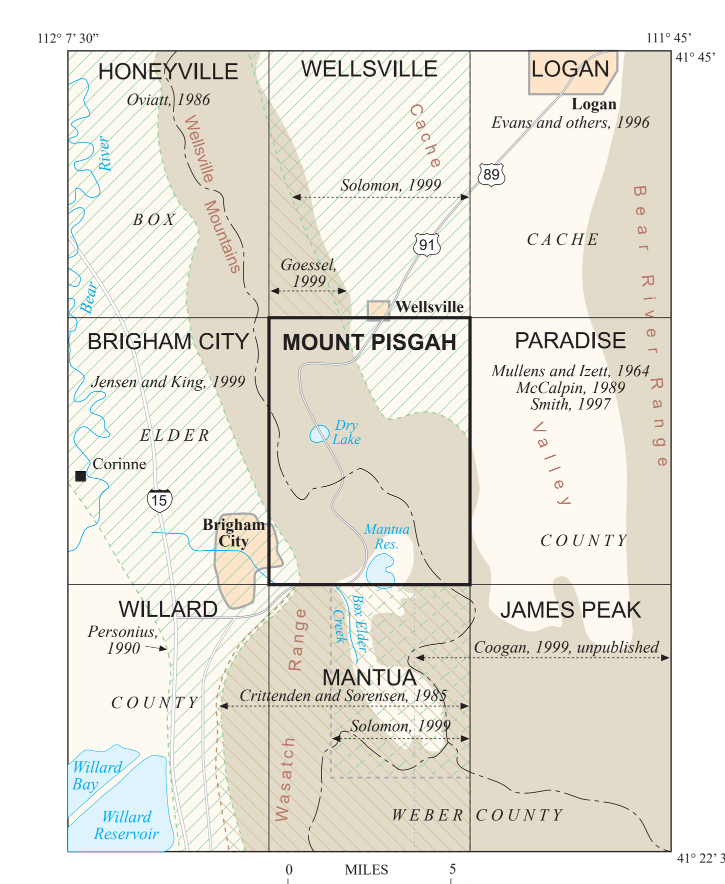


Figure 1. Location and index map for the Mount Pisgah quadrangle, showing adjacent quadrangles and references for geologic mapping.

INTERIM GEOLOGIC MAP OF THE MOUNT PISGAH QUADRANGLE, BOX ELDER AND CACHE COUNTIES, UTAH

by

Jon K. King[1], Barry J. Solomon[2], and Robert Q. Oaks, Jr.[3]

[1]Utah Geological Survey
[2]Retired Utah Geological Survey
[3]Professor Emeritus, Geology Department, Utah State University, Logan, Utah

Disclaimer

This geologic map was funded by the Utah Geological Survey and U.S. Geological Survey, National Cooperative Geologic Mapping Program through U.S. Geological Survey STATEMAP Agreement Number 07HQAG0141. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

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UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
2018

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SUMMARY

The Mount Pisgah quadrangle is located in Box Elder and Cache Counties, Utah, in the high growth northern Wasatch Front urbanized area (figure 1). Cache Valley is in the northeast part of the quadrangle and the U.S. Highway 89-91 transportation corridor runs through the quadrangle. Wellsville is on the north margin of the map area and part of Brigham City is in the southwest corner of the quadrangle.

The Mount Pisgah quadrangle is mostly on the Wellsville Mountains, an east-dipping homocline of Precambrian and Paleozoic rocks on the Willard thrust sheet. The Willard thrust sheet is the western and oldest of several such sheets in the Cretaceous to Eocene "overthrust" belt of Utah, Idaho, and Wyoming (Coogan, 1992; Royse, 1993), and is part of the Cordilleran fold-and-thrust belt of North America (see for example Camilleri and others, 1997). More than 25,000 feet (7600 m) of Proterozoic metasedimentary and mostly marine Cambrian through Permian(?) sedimentary strata are exposed in the homocline. The homocline is unconformably overlain by Tertiary sedimentary rocks, with intra-Tertiary unconformities, and another unconformity separating bedrock from Quaternary surficial deposits. Most of the surficial (Quaternary) deposits in Cache Valley and near Brigham City are related to late Pleistocene Lake Bonneville; surficial deposits in the Wellsville Mountains are at least locally older.

The Wellsville Mountains and the homocline are bounded by normal faults on the west and east, with the Brigham City segment of the Wasatch fault zone in the southwest corner of the Mount Pisgah quadrangle and the West Cache fault zone in the northeast part of the quadrangle. These roughly north-south-trending normal fault zones are due to post-thrust extension, possibly including Oligocene relaxation (collapse) of the Cordilleran fold-and-thrust belt (see Constenius, 1996), as well as documented Miocene and younger Basin and Range extension (see for example McCalpin, 1993). These fault zones have been active in the Quaternary and they represent geologic hazards (McCalpin, 1994; Black and others, 2000; McCalpin and Forman, 2002; DuRoss and others, 2012). Evans and Oaks (1996) indicated that the West Cache fault zone is not visible on a seismic line in southern Cache Valley that they interpreted. However, this seismic line appears to be located on the north margin of the Mount Pisgah and Paradise quadrangles where segments of the West Cache fault zone have limited offset because the fault zone "steps" east (and apparently south) from Wellsville to the eastern edge of the Mount Pisgah quadrangle. Scattered outcrops of Salt Lake Formation and shallow depths to Salt Lake Formation in water wells (after Utah Division of Water Rights website) in the northeast part of the map area support a Tertiary bench at this step. Also from water well logs (Utah Division of Water Rights website), a bench of shallow Oquirrh Formation is beneath Quaternary deposits in the southwest corner of the Tertiary bench (sections 22 and 23, T. 10 N., R. 1 W.). South of the east step (and bench), short faults, lineaments, and scattered outcrops of Tertiary tuffaceous strata (Tts?) on Oquirrh Formation (ℙo) seem to indicate normal faulting west of the step and along trend with the West Cache fault zone near Wellsville. These faults(?), however, do not appear to have been active after deposition of unit Tts, and contribute to the paleotopography on the Oquirrh Formation (note west dips near ℙo-Qafo contact; section 36, T. 10 N., R. 1 W. and section 6, T. 9 N., R. 1 E.) rather than offsetting the overlying Pleistocene alluvial fans (Qafo).

Karst is developed on Cambrian through Mississippian strata in the homocline, and is not better developed on specific formations or ages of rock. Karstification is most evident in the map area as large depressions from Mantua Reservoir northwest to the head of Wellsville Canyon, roughly along U.S. Highway 89-91; karst features are more extensive to the south in the Mantua quadrangle. Sullivan and others (1988) considered these depressions to be too large to be produced entirely by dissolution. Sinkholes are also visible in and near the large depressions. This karst terrain is in the recharge area of the Brigham City water supply. The age of the karst is uncertain, but the presence of red conglomeratic strata of Paleocene-Eocene Wasatch Formation on karst terrain to the southeast (Coogan, 2006) and considerable paleo-relief on the Permian(?)-Pennsylvanian Oquirrh Formation in the Mount Pisgah quadrangle indicate Paleocene and/or Mesozoic development. Red depression fill in the Mount Pisgah and Mantua quadrangles might be terra rossa (residual deposits from dissolution) rather than Wasatch Formation strata. Sinkholes in limestone in the Wasatch Formation (Coogan, 2006) indicate some post-Wasatch dissolution. Further dissolution likely took place during wetter periods (lake cycles) in the Pleistocene. In Wyoming, Pleistocene cave development is older than a cave-infall ash that was chemically correlated with the Lava Creek B ash (Stock and others, 2006), which is ^{40}Ar/^{39}Ar isotopically dated at about 640,000 years old (Lanphere and others, 2002). This middle Pleistocene ash is also present in marsh or lacustrine deposits (likely unit Qlam) in a road cut of U.S. Highway 89-91 in a depression north (not south as reported in Sullivan and others [1988, p. 137]) of Dry Lake in the Mount Pisgah quadrangle (C.G. Oviatt, Kansas State University, verbal communication, July 15, 2008).

This quadrangle needed detailed mapping because previous depictions of the structural geology in the homocline (Williams 1948, 1958; Gelnett, 1958, versus Dover, 1995) were at odds. Older reports showed a strong east-northeast–west-southwest fault trend, roughly perpendicular to bed strike, and Dover (1995) showed a strong northwest-southeast fault trend, roughly parallel to bed strike and the nearby Wasatch and West Cache fault zones. Both trends are present in the quadrangle, as are

some north-south-trending faults, but the greatest number are roughly perpendicular to bed strike (crudely orthogonal east-northeast–west-southwest and east-southeast–west-northwest trending faults). These bed-perpendicular faults have apparent strike-slip offset of up to about 1 mile (1.6 km). Offset on northwest-southeast-trending faults is difficult to determine because most are at least partially concealed, possibly due to dominantly normal, dip-slip offset. The most obvious and longest of these faults (and lineaments) is on the west side of the intermontane depressions and extends to the south into the Mantua quadrangle, where offset is apparently greater but strata are omitted rather than repeated. This fault zone is less than 2 miles (3 km) from the Wasatch fault zone near Brigham City. Southwest of Dry Lake, an estimated 1000 feet (300 m) of strata (entire Nounan Formation) need to be repeated across a concealed segment of this fault. Another northwest-southeast-trending fault shows about 600 feet (180 m) of strike-slip offset, and an estimated 1000 feet (300 m) of Laketown-Fish Haven strata are repeated across a fault near Sardine Summit. One of the north-south-trending faults has strike-slip offset of about one-half mile (0.8 km). These offsets are much smaller than to nearly the same as the 0.6-mile (1 km) normal offset on the sub-parallel West Cache fault zone near Wellsville (Evans and Oaks, 1996), but are far smaller than the greater than 2-mile (>3 km) normal offset on the sub-parallel Wasatch fault zone near Brigham City (Jensen and King, 1996).

The Box Elder thrust of Sorensen and Crittenden (1976a,b) in the Proterozoic rocks near Brigham City is more problematic; it actually “places” younger rocks over older rocks, making it a low-angle to bedding, normal fault, possibly formed during Oligocene extension. The Box Elder fault omits about 2500 to 3000 feet (750–900 m) of strata in the Mantua quadrangle, if the mapping of Sorensen and Crittenden (1976a,b) is correct. But where exposed in the Mount Pisgah quadrangle, the Box Elder fault may only eliminate several hundred feet of strata, and to the south in the Mantua quadrangle the Box Elder fault also appears to be a minor feature. The south end of the Box Elder fault near Brigham City appears to terminate at a roughly east-west trending fault with apparent strike-slip offset that is mostly in the Mount Pisgah quadrangle. The problem with the Box Elder “thrust” in the Mantua quadrangle mapping is due to the similar appearances of reddish-weathering Browns Hole and Inkom Formations and of lighter-colored quartzite in the Geertsen Canyon Quartzite and Mutual Formation, and also not recognizing several steeply dipping faults. The Mutual also contains medial argillite beds like those reported by Link and others (1987) in Idaho. Assignment of this argillite to the Browns Hole Formation, the similar lithologies and coloration of parts of the Browns Hole and Inkom Formations, and the similar coloration of the Mutual and Geertsen Canyon quartzites led to confusing map-unit descriptions and geologic-map relationships in previous reports on the Mantua and Mount Pisgah quadrangles (see Sorensen and Crittenden, 1976a,b; Crittenden and Sorensen, 1985); this also led to complex structural interpretations by these authors. North of the roughly northeast-southwest-trending Flat Bottom Canyon fault, which has about 2500 feet (750 m) of strike-slip offset, the Box Elder fault is concealed along the mountain front (Wasatch fault zone) and about 2500 to 3000 feet (750–900 m) of strata appear to be missing between small outcrops in Lake Bonneville deposits and cliffs of Proterozoic quartzite up slope. However, if these small outcrops and those in the Brigham City quadrangle are incorrectly identified (not Zcc and Zpc), only several hundred feet of strata are missing. Link and Smith (1992) implied that this low-angle fault is a late Cenozoic extensional feature, but it is offset by several northeast-trending faults with apparent strike-slip offset that could be due to Cordilleran (Cretaceous-Eocene) compression, Oligocene relaxation, or Basin and Range (late Cenozoic) extension.

This and other geologic mapping in the Wellsville Mountains indicate Devonian strata are omitted by more than one unconformity (compare to Rigby, 1959). In particular, the Beirdneau Sandstone thins to absence to the south, and then farther south the Hyrum Dolomite also disappears (see Oviatt, 1986; Jensen and King, 1996) (figure 2); both are absent in the Mount Pisgah quadrangle. The Hyrum reportedly reappears in the northeast part of the Mantua quadrangle (Ezell, 1953; Crittenden and Sorensen, 1985), with an underlying, thin (<100 feet [30 m]) recess of white- and orange-weathering Water Canyon. Their resistant, dark-weathering Hyrum is about 100 feet (30 m) thick where it reappears (but is actually Water Canyon strata), though the Hyrum is about 400 feet (120 m) thick farther to the south (after Coogan and King, 2016). Faulting and problems with unit identifications mean the Water Canyon is at least 400 feet (120 m) thick in the Mantua quadrangle where not faulted. The Beirdneau absence indicates an upper Devonian unconformity in addition to the mid-Devonian unconformity/uplift shown by Rigby (1959). Crittenden and Sorensen (1985) and Coogan and King (2001) showed a fault contact between Silurian (Sl) and Mississippian (Ml) strata on the north margin of the Mantua quadrangle. However, it is more complicated as the fault splits into several strands. Two fault strands actually continue on trend to the north into the Mount Pisgah quadrangle, after negligible offset across a roughly east-west trending fault in the Mantua quadrangle. This cross fault is mostly in a drainage and covered, but is visible upslope in offset of the Delle Phosphatic Member of the Little Flat Formation just inside the Mount Pisgah quadrangle. The two other strands appear to end at this cross fault just south of the Mount Pisgah quadrangle, and bound Water Canyon Formation exposures. So, all the Water Canyon members extend into the Mantua quadrangle, but are fault thinned and abut Laketown Dolomite (Sl) and Lodgepole Limestone (Ml) at fault contacts. Other complications are that, as mapped by Crittenden and Sorensen (1985) and Coogan and King (2001), the Water Canyon is only about one-tenth as thick in exposures 1.5 miles (2.5 km) to the east, where their Hyrum is mapped; however, the lower member of the Water Canyon is included, at least locally, in their Laketown. From reconnaissance mapping for this project, their Water Canyon Formation is part of the lower member and their Hyrum includes the resistant middle member, and locally, the swale-forming upper member of the Water Canyon. Therefore, the Hyrum is absent in most of the Mantua quadrangle, but is exposed west of Sink Valley (see Coogan and King, 2016). Still, unfaulted Water Canyon Formation in the Mantua quadrangle is about one-third the total thickness in the Mount Pisgah quadrangle (Coogan and King, 2016); where and how the thinning occurs has not been determined.

The diagrams of Rigby (1959, figures 1 and 2), which show the Devonian Stansbury uplift, need refinement on and near the Willard thrust sheet, and some of what he shows is the product of the Ordovician Tooele arch (see Hintze, 1959). The diagrams of Rigby (1959) also need refinement because lower Devonian (Water Canyon) rocks are thinned below an unconformity (and Hyrum carbonates) to the south at Ogden Canyon (Yonkee and Lowe, 2004), and to the east in the Monte Cristo Range (Smith, 1961; Coogan, 2006), as well as farther south and east at Causey Dam (Mullens, 1969) and Durst Mountain (Coogan and King, 2006).

The surficial geology of most of the Mount Pisgah quadrangle was photogeologically mapped by King at 1:24,000 scale. Mapping in the northeast part of the quadrangle and in intermontane depressions was modified from Solomon's (1999) smaller scale (1:50,000) surficial geologic map of the West Cache fault zone. Surficial geology in the southwest corner of the quadrangle, near Brigham City, was modified from the 1:50,000-scale map of Personius (1990) that focused on the Wasatch fault zone. Most of the bedrock was photogeologically mapped by King at a scale of 1:24,000, with limited field checks; contacts were traced into the quadrangle from the Brigham City quadrangle (Jensen and King, 1996) to the west and the Mantua quadrangle (Coogan, 1999, unpublished 1:24,000-scale mapping, simplified on Coogan and King, 2016) to the south. The contacts on this map do not match those at the common border with the Brigham City quadrangle because the orthophotograph used to construct the Brigham City map was flawed. Bedrock in the southwest corner of the quadrangle is modified from Sorensen and Crittenden (1976b) and bedrock mapping of Jensen and others (1995) north of Mantua was consulted. Tertiary bedrock mapping by Smith and Oaks (1997) in the east part of the quadrangle was consulted after our initial mapping. Robert J. Oaks also graciously provided King copies of his mapping on aerial photographs, gravity data (including profiles and contour maps), and his interpretations of water-well logs (including cross sections). Though we disagree on some interpretations, these data improved this map and report. Further, as work progressed on the Mount Pisgah geologic map, I (King) found my mapping became more like that of Oaks. Still, the contacts on our map are based on field checks by King and are not the same as Oaks' contacts (interpretations).

In particular, we still disagree on mapping south of Quaking Aspen Hollow (NE1/4 section 8 and NW1/4 section 9, T. 9N., R. 1W.), where plate 1 shows landslides (Qms, Qms blocks), per King's interpretation. Oaks interprets these as in place bedrock, which would require a down-to-the-west normal fault and complex geologic structure. This complexity and the other landslide blocks in the quadrangle led King to interpret the exposures as landslides.

Quaternary geologic mapping by McCalpin (1989) to the east in the Paradise quadrangle was also consulted; however, because he concentrated on the East Cache fault zone, contacts on the Mount Pisgah map do not match his map. Surficial map-unit descriptions and thicknesses are modified from Personius (1990) and Solomon (1999); see also McCalpin (1989). Bedrock map-unit descriptions and thicknesses are mostly modified by King from Jensen and King (1996).

The best available detailed geologic maps in the adjacent 7.5-minute quadrangles are shown on figure 1. Other unpublished maps in the Mantua and James Peak quadrangle are the Utah State University thesis maps of Ezell (1953), Blau (1975), and Rauzi (1979). Many other geologic studies are cited in the following descriptions of map units. Because this report does not cover all aspects of the geology of the Mount Pisgah quadrangle, other references are appended to the cited references.

DESCRIPTION OF SURFICIAL (QUATERNARY) MAP UNITS

Lacustrine and Deltaic Deposits

These sediments were mostly deposited during the last Pleistocene lake cycle (late Pleistocene Lake Bonneville), with some deposition in younger lakes and marshes (Holocene). For a review of the Bonneville lake cycle, in particular the chronology, see Oviatt and others (1992). Quaternary dates used in this report are in carbon-14 years (^{14}C yr B.P.) unless otherwise noted. Lacustrine deposits in the map area are divided by age into four groups: (1) deposits that post-date Lake Bonneville (younger than about 12,000 years), located in intermontane ephemeral lakes and present-day marshes (sloughs); (2) deposits associated with the Provo level of Lake Bonneville and regression from this level (about 14,500 to 12,000 years), located topographically below the Provo shoreline; (3) deposits associated with the Bonneville level of Lake Bonneville and transgression of Lake

Bonneville to this, the highest level (about 30,000 to 14,500 years), located topographically below the Bonneville shoreline and, typically, above the Provo shoreline; and (4) undivided Lake Bonneville deposits, those that cannot be assigned to a specific phase of Lake Bonneville, located topographically below the Provo shoreline (30,000 to 12,000 years). Lacustrine sediments deposited near mountain fronts are mostly gravel and sand, and include the delta east of Brigham City. Silt and clay were deposited in quieter, deeper water in Lake Bonneville in Cache Valley and near Brigham City, and, less commonly, in lagoons behind barrier beaches. When Lake Bonneville was near its highest, it extended up Box Elder Canyon into Mantua Valley. The Bonneville shoreline is at 5174 feet (1577 m) in Baxter Pothole lagoon bar (Currey, 1982), a constructional feature in Cache Valley, and, as is typical, the erosional shorelines is at a higher elevation of about 5180 feet (1579 m) in Cache Valley. The Bonneville shoreline is at about 5180 to 5200 feet (1579–1585 m) in erosional shorelines near Brigham City. The constructional Provo shoreline is at 4810 feet (1466 m) in the southernmost part of Sterling bar southwest of Mount Sterling Cemetery (after Currey, 1982), and, as is typical, is at about 4820 feet (1470 m) in an erosional shoreline near the cemetery. Erosional Provo shorelines are lower near Wellsville, at 4780 to 4800 feet (1457–1463 m), and are at 4820 to 4840 feet (1470–1475 m) near Brigham City. Part of the variation in shoreline elevations is likely tectonic, due to movement on the West Cache and Wasatch fault zones, though part of the variation in Provo shoreline elevations near Brigham City is because the shoreline is indistinct on the Provo-level delta at the mouth of Box Elder Canyon and on the steep mountain front.

Deposits younger than Lake Bonneville (Holocene to uppermost Pleistocene)

Qlm **Lacustrine and marsh deposits** – Silt, clay, and minor sand deposited in intermontane ephemeral lake in Dry Lake depression north of Sardine Summit (name not on newer topographic maps); this depression floods periodically; estimate 3 to 10 feet (1–3 m) thick. Under Mantua Reservoir these fine-grained deposits may overlie, grade into, and/or be reworked from Lake Bonneville sediment, and/or may be Lake Bonneville sediment.

Deposits associated with Provo shoreline and later regression of Lake Bonneville (uppermost Pleistocene)

Qdp **Deltaic deposits** – Clast-supported pebble and cobble gravel in a matrix of sand and minor silt, interbedded with thin sand beds and grading downslope to silt and fine sand in the distal (bottom-set bed) portion of delta; clasts subrounded to rounded; weakly cemented by calcium carbonate; moderately to well sorted within beds. Deposited as foreset beds with original dips of 30 to 35 degrees and as bottomset beds with original dips of 1 to 5 degrees; exposed thickness in gravel pits near Brigham City about 80 feet (25 m); capped with gently dipping topset beds of less well sorted, silty to sandy, pebble and cobble gravel that are less than 15 feet (5 m) thick; some topset beds grade upslope into alluvial deposits. Much of material may have been redeposited from Bonneville-level lacustrine and alluvial deposits during and soon after the Bonneville flood; includes deltas graded to regressional stillstand lake levels below the Provo shoreline.

Deposits east of Wellsville in the distal Little Bear River delta, in northeast corner of map (see also McCalpin, 1989) are finer grained than other deltaic deposits in the map area, as is characteristic of distal/bottom-set beds.

A delta is also present at the mouth of Wellsville Canyon; the portion above a mappable regressional shoreline (r) is mapped as fan-delta (Qadp) while that below this shoreline is mapped as Qdp. Deltaic deposits are about 140 feet (45 m) thick in a well near mouth of Wellsville Canyon (SW1/4 SE1/4 section 10, T. 10 N., R. 1 W.) (after Utah Division of Water Rights website).

Deltaic deposits (Qdp) mapped below the Provo shoreline east of Brigham City at the mouth of Box Elder Canyon contain more gravel than sand and have been extensively excavated for production of sand and gravel. King (in Jensen and King, 1996) estimated these deltaic deposits are about 250 feet (75 m) thick, while Smith and Jol (1992) implied they are 400 feet (120 m) thick; Personius (1990) reported about 80 feet (24 m) of topset and foreset beds are exposed in the Mount Pisgah quadrangle.

Qlgp **Lacustrine gravel and sand** – Pebble and cobble gravel in a matrix of sand and silt; varies from clast supported to only rare gravel clasts; commonly interbedded (sometimes rhythmically) with thin sand beds and laterally gradational into lacustrine sand (Qlsp); well sorted within beds; clasts commonly subrounded to rounded, but some shorelines along steep mountain fronts marked by a poorly sorted beach conglomerate consisting of angular boulders and locally a calcium-carbonate-cemented matrix; thin to thick bedded; original bedding dips vary from 0 to 10 or 15 degrees on steep piedmont slopes or in constructional landforms such as beach ridges, bars, and spits. Present along and below the Provo shoreline, grading downslope and laterally in Cache Valley into deposits of map unit Qlsp; east of Brigham City, unit likely consists of a thin veneer of regressional shoreline deposits over transgressional lacustrine deposits (see Personius, 1990); typically forms eroded bench at the highest Provo shoreline and wave-built ridges at several less well-developed shorelines at lower elevations; typically partly covered by colluvium and talus on mountain fronts, though these mass-movement deposits are typically indistinct or too small to show at map scale; Qac locally forms mappable accumulations on Provo shoreline bench near Brigham City; most prominent constructional landform of unit Qlgp is Sterling bar (Williams, 1962) that crosses the south end of Cache Valley south of Wellsville; exposed thickness less than 15 feet (5 m), but about 25 feet (7 m) thick in subsurface in well southeast of Mount Sterling (SW1/4 section 14, T. 10 N., R. 1 W.), and about 30 to 50 feet (10–15 m) thick in subsurface in wells on spit north of lagoon (unit Qlfp) on north border of map area (SW corner section 1 and NW corner section 12, T. 10 N., R. 1 W.) (after Utah Division of Water Rights website). This spit may be cored by Salt Lake Formation at depths of less than 100 feet (30 m) (after Utah Division of Water Rights website), note possible shallow Salt Lake Formation (Qlgp/Ts?) on border between sections 11 and 12.

Qlsp **Lacustrine sand and silt** – Coarse to fine sand, silt, and clay; well sorted within beds; thin bedded, with rhythmic bedding and ripple laminations common; original bedding dips vary from 0 to 10 degrees; only mapped in Cache Valley. Deposited near shore during regression of Lake Bonneville; generally overlies/conceals fine-grained, deeper-water silt and clay deposited during transgression to and the stillstand at the Bonneville shoreline, and grades downslope into silt and clay (not exposed in map area); forms beaches, bars, and spits where longshore current and sediment supply were adequate; typically sand poor where not in these constructional landforms; present along and below the Provo shoreline, downslope of the Sterling bar near Wellsville; exposed thickness less than 10 feet (3 m).

Qlfp **Fine-grained lacustrine deposits** – Predominantly calcareous silt (commonly referred to as marl) with minor clay and fine sand; apparent bedding is thick to unstratified, but commonly rhythmic on close inspection. Deposited in a quiet-water environment, a sheltered bay or lagoon behind a spit east of Wellsville on north margin of map; shorelines not developed on this unit; exposed thickness less than 5 feet (1.5 m).

Deposits associated with the transgression of Lake Bonneville and the Bonneville shoreline (upper Pleistocene)

Qlb **Undivided deposits** – Includes sand and silt, and possibly gravel; mapped in Mantua Valley near Bonneville shoreline; on surface, grain size is indistinct, but should be gravelly; deposits are not exposed by construction; locally overlain (and likely underlain) by alluvial-fan gravels; thickness uncertain. Qla mapped in Mantua Valley where shoreline not visible.

Qdb **Deltaic deposits** – Pebble and cobble gravel in a matrix of sand and minor silt; interbedded with thin sand beds; moderately to well sorted within beds; clasts sub-angular to subrounded; deposited as foreset beds with original dips of 30 to 35 degrees; only mapped at mouth of Flat Bottom Canyon; exposed thickness less than 50 feet (15 m).

Qlgb **Lacustrine gravel and sand** – Pebble and cobble gravel in a matrix of sand and silt; varies from clast supported to only rare gravel clasts in Cache and Mantua Valleys; interbedded with pebbly sand; well-sorted within beds; thin to thick bedded; original bedding dips vary from 0 to 15 degrees and 25 degrees on steep piedmont slopes or in constructional landforms such as beach ridges, bars, and spits; clasts commonly subrounded to rounded, but shorelines along steep mountain fronts locally marked by a poorly sorted beach conglomerate consisting of angular to subangular boulders as much as several meters in diameter in a sandy, calcium-carbonate-cemented matrix; typically partly covered by colluvium and talus on mountain fronts, with greater and locally mappable accumulations on Bonneville shoreline benches. Deposited in beaches, bars, and spits between the Bonneville and Provo shorelines, but mostly just downslope from Bonneville shoreline; grades downslope and, locally, laterally into unit Qlsb in Cache Valley; in Cache Valley typically gravel poor where downslope, and away from, constructional landforms; typically forms erosional benches at the Bonneville shoreline, and several less well developed intermediate (transgressive-t) shorelines; locally forms beach ridges/constructional shorelines; exposed thickness less than 20 feet (6 m). Estimate 25 feet (8 m) thick in subsurface in well southeast of Mount Sterling (SW1/4 section 14, T. 10 N., R. 1 W.) and seems to be about 85 feet (25 m) thick upslope closer to Bonneville shoreline on knob southeast of Lindleys Basin (NE1/4 section 22, T. 10 N., R. 1 W.) (after Utah Division of Water Rights website). Thickness in Mantua Valley uncertain (see logs in Bjorklund and McGreevy, 1973, p. 16, and Utah Division of Water Rights website).

Qlsb **Lacustrine sand and silt** – Coarse to fine sand, silt, and clay; typically rhythmically bedded; well sorted within beds; ripple laminations common; original bedding dips vary from 0 to 10 degrees. Deposited as nearshore sediments in beaches and spits, and as lagoon fill behind barrier bars; not mapped near Brigham City; typically sand poor where not in beaches and spits, which is most of this quadrangle; locally grades laterally into unit Qlgb; mapped between sand and gravel of unit Qlgb upslope and the Provo shoreline downslope in Cache Valley; exposed thickness less than 10 feet (3 m).

Qllb **Fine-grained lacustrine lagoon deposits** – Predominantly calcareous silt (commonly referred to as marl), with minor clay and fine sand; thick bedded to unstratified; deposited in small lagoons south and west of Wellsville, and in lagoon to the east at Baxter Pothole; queried where likely coarser grained in Flat Bottom Canyon east of Brigham City (sand and gravel), and northwest of Baxter Pothole (should be overlain by Qlsb); exposed thickness less than 5 feet (1.5 m).

Deposits of Lake Bonneville, undivided (upper Pleistocene)

Ql **Undivided deposits** – Includes gravel, sand, silt, and clay in Cache Valley; mapped where grain size is mixed or indistinct and deposits are not exposed in scarps or construction cuts; typically underlain by shallow Salt Lake Formation (shown as Ql/Ts); thickness uncertain.

Qlg **Lacustrine sand and gravel** – Sand and clast-supported, rounded pebble gravel in matrix of sand and silt; mapped downslope from the Provo shoreline at the base of the mountain front near Brigham City where these deposits are offset by the Wasatch fault zone and cannot be directly correlated to regressional shorelines; exposed thickness less than 15 feet (5 m).

Stream Alluvium

Stream deposits are mapped in floodplains and terraces along perennial and some intermittent streams; gravel in these deposits generally is more rounded and better sorted than in equivalent-age alluvial-fan deposits. Stream deposits are differentiated by their vertical positions relative to present-day/active streams and to shorelines of Lake Bonneville.

Qal **Stream alluvium** (Holocene and uppermost Pleistocene) – Pebble and cobble gravel, gravelly sand, silty sand, and minor clay that were deposited after regression of Lake Bonneville from the Provo shoreline; contains thin sand lenses; moderately sorted; clasts subangular to rounded; thin to medium bedded. Deposited by perennial streams such as the Little Bear River (in the northeast corner of map area) and along drainages into Cache Valley, like Wellsville and Sardine Canyons; also deposited along Box Elder Creek, Dam Creek, and Skunk Hollow in southwest part of map area; stream alluvium in Mantua Valley is finer grained than other alluvium; locally includes minor sheetwash (colluvium) and mass-wasting (slump) deposits near steep stream embankments, alluvial fans, and terraces too small to show at map scale; some deposits grade up and down drainage into alluvium and colluvium (Qac). Mapped in floodplains and low terraces less than 15 feet (5 m) above present-day/active streams; floodplains characterized by active stream channels; exposed thickness less than 10 feet (3 m) and about 15 feet (5 m) thick in subsurface in well at Mount Sterling (NE1/4 section 15, T. 10 N., R. 1 W.) (after Utah Division of Water Rights website).

Qat **Stream-terrace alluvium** (middle Holocene to upper Pleistocene) – Pebble and cobble gravel, gravelly sand, silty sand, and minor clay; contains thin sand lenses; clasts mostly subangular; mapped along several drainages in east part of map area; terrace surfaces 10 to more than 20 feet (3–6+ m) above present-day drainages; exposed thickness up to about 20 feet (6 m).

Qatp **Stream-terrace alluvium related to Provo shoreline** (uppermost Pleistocene) – Pebble and cobble gravel, gravelly sand, silty sand, and minor clay; contains thin sand lenses; moderately sorted; clasts subangular to rounded; thin to medium bedded; deposited by streams graded to the Provo shoreline (unit Qlgp) at Narrow Canyon; exposed thickness less than 15 feet (5 m).

Alluvial-Fan Deposits

Alluvial-fan deposits are typically at the mouths of most canyons in the map area and deposits are thickest near the mountain fronts, such as on the downthrown, west side of the Wasatch fault zone, and the east side of the fault zone in the Wellsville Mountains. Fans were deposited by perennial and intermittent streams, mudflows, debris flows, and debris floods. The sediment is commonly poorly sorted with a matrix-supported framework. Fan deposits are typically differentiated by (1) their positions relative to shorelines of Lake Bonneville and other alluvial deposits, (2) their height above present-day streams, (3) degree of soil development, and (4) differences in morphologic expression, such as sharpness of debris flow levees and channels, and/or degree of dissection. We did not map debris-flow deposits separately from alluvial-fan deposits, because some borders of debris-flow deposits near Brigham City are indistinct, such that contacts could not be completely mapped, and alluvial fans typically include debris-flow deposits.

Qaf **Fan alluvium, undivided** (Holocene and Pleistocene) – Poorly sorted, angular boulders, cobbles, pebbles, sand, silt, and clay that were deposited in intermontane valleys in the Wellsville Mountains; age undivided since fans coalesced and elevations are above Lake Bonneville shorelines; unit includes active alluvial fans, older Holocene, and latest Pleistocene (post-Provo shoreline) alluvial fans (Qafy); Lake Bonneville alluvial fans (Qafp, Qafb); and pre-Lake Bonneville alluvial fans (Qafo). In subsurface in the map area, reportedly 120 feet (36.5 m) thick at mouth of Snow Canyon north of Dry Lake (Williams and others, 1970, in Rice, 1987, p. 55), about 100 feet (30 m) thick in section 22, T. 9 N., R. 1 W. northwest of Mantua, and about 150 feet (45 m) thick beneath Qac in sections 9 and 16, T.9 N., R.1 W. (Utah Division of Water Rights website); potentially much thicker, see subsurface thickness of Qafo.

Qaf1 **Holocene fan alluvium** (upper Holocene) – Mapped near Brigham City, forming small, discrete fans derived from gravelly lacustrine and deltaic deposits of Lake Bonneville; contain pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; poorly sorted with angular to rounded clasts; rounded clasts of Lake Bonneville gravel (Qlg, Qlgp, Qlgb) common; medium to thick bedded to unstratified; deposited by/along present-day intermittent streams; locally includes debris-flow and -flood deposits and areas of somewhat older alluvial fans (unit Qaf2) that are too small to show separately at map scale; no shorelines of Lake Bonneville are present on this unit; distinguished from Qaf2 by sharpness of debris-flow levees and channels; exposed thickness less than 10 feet (3 m), typically thinning downslope.

Qaf2 **Post-Lake Bonneville fan alluvium** (middle Holocene to uppermost Pleistocene) – As mapped near Brigham City, no shorelines of Lake Bonneville are present on this unit and graded to near present-day stream levels; contains pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and minor clay; poorly sorted; clasts angular to subrounded, with some rounded clasts of Lake Bonneville gravel (Qlg, Qlgp, Qlgb); medium to thick bedded to unstratified; locally includes debris-flow and -flood deposits and areas of younger alluvial fans (unit Qaf1) that are too small to show separately at map scale; distinguished from Qaf1 by subdued debris-flow levee morphology; exposed thickness less than 15 feet (5 m), typically thinning downslope.

Qafy **Younger fan alluvium, undivided** (Holocene to uppermost Pleistocene) – Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and clay; sorting and clast angularity depend on source area, so gravels derived from bedrock are more poorly sorted and more angular than gravels eroded from lacustrine deposits (see units Qaf1 and Qaf2); includes some small fans derived from rounded gravelly Lake Bonneville deposits; younger fan alluvium postdates regression of Lake Bonneville from the Provo shoreline and many younger fans are active; no shorelines of Lake Bonneville are present on surfaces of this unit; likely include debris-flood and -flow deposits too small to show at map scale. Mapped in areas where active and slightly older fans (like Qaf1 and Qaf2) complexly overlap, are too small to show separately at map scale, or the specific age of these alluvial-fan units has not been determined; exposed thickness in map area less than 15 feet (5 m), but at least 35 feet (11+ m) thick in subsurface near Brigham City (Jensen and King, 1996).

Qafp **Fan alluvium related to Provo shoreline** (uppermost Pleistocene) – Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and clay; poorly to moderately sorted; clasts angular to rounded, with well-rounded recycled Lake Bonneville gravel; medium to thick bedded to unstratified; deposited by streams associated with the Provo shoreline below Bott Canyon northeast of Brigham City; likely less than 10 feet (3 m) thick.

Qafb **Fan alluvium related to Bonneville shoreline** (upper Pleistocene) – Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and clay; poorly sorted; clasts angular to subangular; medium to thick bedded to unstratified; deposited in Flat Bottom Canyon, upstream from a barrier bar; covered by thin deposits of younger alluvium and colluvium; exposed thickness less than 15 feet (5 m); see also Personius (1990).

Qafo **Older fan alluvium, undivided** (upper to lower Pleistocene; pre-Lake Bonneville) – Pebble and cobble gravel, locally bouldery, in a matrix of sand, silt, and clay; poorly sorted; clasts angular to subrounded and derived from bedrock in adjacent drainages, with no Lake Bonneville gravel; some fans in intermontane depressions derived from tuffaceous Tertiary rocks, though Tertiary strata are not adjacent, and consequently look like Tertiary strata; medium to thick bedded to unstratified; not equivalent to Qafo that Jensen and King (1996) mapped in Brigham City quadrangle. Though dissected, older fans typically lack distinct geomorphic expression, except for location above the Bonneville shoreline; typically incised 0 to 40 feet (0–12 m) and locally more than 100 feet (30+ m) by active drainages; locally incised 40 to 80 feet (12–25 m) in intermontane basins. Exposed thickness up to about 100 feet (30 m), but water wells in sections 26 and 27, T. 9 N., R. 1 W. just south of the quadrangle were still in gravelly to bouldery valley fill at depths of 505 and 467 feet (154 and 142 m), respectively, though red coloration was not noted (see Bjorklund and McGreevy, 1973, p. 16). As mapped only slightly truncated at Bonneville shoreline; shoreline mappable north and locally east of Mantua Reservoir.

The reddish gravels that underlie Lake Bonneville deposits in wells near Wellsville (section 10, T. 10 N., R. 1 W.) and southeast of Mount Sterling (SW1/4 section 14, T. 10 N., R. 1 W.) (after Utah Division of Water Rights website) could be part of this unit and/or could be some older alluvial deposits like those mapped by Goessel (1999; her QTa) to the north. These gravels are noted as being derived, in part, from the Wasatch Formation, with possible Wasatch Formation in the deeper wells near the center of section 10. In section 14, these reddish gravels are about 100 feet (30 m) thick and apparently overlie green Salt Lake and/or Norwood Formation strata (after Utah Division of Water Rights website). As noted in the Tertiary map-unit descriptions, reddish units are problematic and are likely more than one age. Given the age of unit Qafo, it is important to note the likely middle to early Pleistocene terra rossa development during karstification; the karst age is based on the Lava Creek B ash (640,000 years old [Lanphere and others, 2002]) in the intermontane basin north of Dry Lake.

Still older fans may be present in Cache Valley in the southeast part of the Mount Pisgah quadrangle; the more deeply incised fans (40–80 feet [12–25 m] above adjacent drainages) in intermontane depressions might also be older. Bedrock knobs, mostly Oquirrh Formation with considerable paleotopography, are presently being exhumed from the fans in the southeast part of the map area and a gravel-armored surface (flat and possible fan remnant) is present on the Salt Lake Formation in the southeast corner of the quadrangle; it is better developed to the east in the Paradise quadrangle. The fans are typically incised more than 40 feet (12 m) and locally up to 100 feet (30 m) by active drainages. Overall the gravel-armored surface is at a higher elevation than the McKenzie Flat geomorphic surface of Williams (1948) on McKenzie Flat (~5800–6000 feet [1770–1830 m] versus ~5400–5600 feet [1650–1710 m]), but might be related because several faults have been mapped between the two flats to the south in the James Peak quadrangle (see Coogan and King, 2016).

McKenzie Flat forms a gently north-inclined, little-dissected bench capped by older fans in the eastern Paradise and James Peak quadrangles; variably dissected surfaces of eroded remnants of these older fans dip west from the East Cache fault zone to the flat. McCalpin (1989) described the fans on McKenzie Flat as a thin, less than 10 meter (33 ft) thick, discontinuous veneer on a surface (pediment) “cut” on Tertiary Salt Lake Formation; see also Mullens and Izett (1964, p. 14–15).

The surface and the older fans in the southeast part of the Mount Pisgah quadrangle (and adjacent western Paradise quadrangle) could be middle Pleistocene (McCalpin, 1989; see also Sullivan and Nelson, 1992) and/or early Pleistocene (after Sullivan and others, 1988) in age if correlative with the McKenzie Flat surface of Williams (1948). However, in the east part of the Paradise quadrangle, the older fans and McKenzie Flat surface are typically incised to a far greater depth, greater than 50 to 1000 feet (>15 to 300 meters), than the older fans in the Mount Pisgah quadrangle.

Mass-Movement Deposits

These deposits consist of poorly sorted to unsorted, typically unstratified, gravity-induced deposits; composition of clasts reflects the materials from which they were derived.

Qc **Colluvium** (Holocene to upper Pleistocene) – Pebble-, cobble-, and boulder-sized gravel, gravelly sand, sand, silt, and clay; commonly unsorted and unstratified except for a basal concentration of clasts; clasts commonly angular to subangular, rarely containing rounded gravel from Lake Bonneville deposits. Mapped in and near Box Elder Canyon, Wellsville Canyon, Cookys Hollow, Babbit Shanty Hill, McMurdie Hollow, and several other sites where deposits are coarser grained and derived from Paleozoic rocks by slope wash, creep, and other mass-wasting processes on moderate to steep mountain slopes. Includes other mass-wasting (debris-flow, talus, slump, and landslide) deposits too small to show separately at map scale; exposed thickness less than 15 feet (5 m).

Qct **Colluvium and talus** (Holocene and upper Pleistocene) - Angular debris at the base of and on steep, typically unvegetated slopes; prominent on north side of Wellsville and Box Elder Canyons; estimate 0 to 10 feet (0–3 m) thick.

Qmt **Talus deposits** (Holocene to upper Pleistocene) – Poorly sorted to unsorted, unstratified, angular to subangular, boulder- to pebble-size rock rubble, commonly clast supported, in a sparse sand and silt matrix, especially near surface of deposit; derived from Cambrian quartzite (Cgl) by rock fall, slope wash, and creep on steep mountain slopes northeast of Brigham City; exposed thickness less than 10 feet (3 m).

Qmc **Mass-movement and colluvial deposits, undivided** (Holocene and Pleistocene) – Mapped where landslides and slumps are difficult to distinguish from colluvium (slopewash and soil creep) and where mapping separate, small, intermingled areas of mass-movement and colluvial deposits is not possible at map scale; locally includes talus and debris flows; typically mapped where landslides and slumps are thin (“shallow”); also mapped where the blocky or rumpled morphology of older (likely Pleistocene) mass movements has been diminished (“smoothed”) by slopewash and soil creep; composition depends on local sources; 0 to 40 feet (0–12 m) thick. This unit is likely as unstable as Qms units.

Qmsy **Younger landslide deposits** (Holocene to upper Pleistocene) – Unsorted, unstratified gravel, sand, and silt; typically slumps and flows with disruption or cover of Lake Bonneville deposits; exposed thickness less than 25 feet (8 m). Slumps and flows of deltaic sand (unit Qdp) along the Little Bear River in northeast corner of map area formed after Holocene incision of the river to its present level. Several of these deposits are above Bonneville shoreline, so age uncertain.

Qms **Landslide and slump deposits, undivided** (Holocene to middle Pleistocene) – Unsorted, unstratified deposits of gravel, sand, silt, and bedrock blocks in slides, slumps, and flows, typically on and below moderately steep slopes; deposits in Tertiary strata (Tw, Tf?, Tn?, Tcg, Tts, Ts, Tscg) are commonly shallow debris slides and rotational slumps; undivided deposits are above the Bonneville shoreline and their age relation to Lake Bonneville is therefore unclear; exposed thickness typically less than 25 feet (8 m), but the largest block slide is an estimated 600 feet (180 m) thick. The largest slides and slumps are block slides of Paleozoic sedimentary rocks, mapped in the Wellsville Mountains at Stoddard Hill (in the Mississippian Little Flat Formation), near Snow Canyon (in the Devonian Water Canyon Formation), and near Mahogany Canyon (in Cambrian shales). A large slide originating in the Precambrian Papoose Creek Formation east of Brigham City has undergone multiple movements; the latest postdates the Provo shoreline (Personius, 1990). Unit Qafo is particularly prone to slides/slumps/flows because of the reworked/altered tuff in the deposits. Qms may be mapped in contact with Qms where discrete slides/slumps/flows abut. Locally, unit involved in slide/slump is shown in parentheses where a nearly intact block is visible. Qms queried where block may not be a mass movement.

Qmso **Older landslide deposit** (upper and middle Pleistocene) – Unsorted, unstratified deposits of gravel, sand, and silt; only mapped on north side of Baxter Ridge where Bonneville shoreline is “etched” on slide; thickness likely less than 10 feet (3 m). This unit is likely as unstable as other Qms units.

Mixed Deposits

Qlam **Lacustrine, marsh, and alluvial deposits, undivided** (Holocene to uppermost Pleistocene) – Sand, silt, and clay in areas of mixed lacustrine, marsh, and alluvial deposits; mostly younger than Lake Bonneville, but unit may contain Lake Bonneville-age sediment. Mapped in intermontane depressions north of Mantua Reservoir; Lava Creek B ash likely in this unit in depression north of Dry Lake or in thin marsh/lake deposits in unit Qafo; typically 3 to 10 feet (1 to 3 m) thick. Marshy area on north margin of map east of Wellsville mapped as this unit, though no alluvial deposits are present at this site.

Qla **Lake Bonneville and post- and pre-Lake Bonneville alluvial deposits, undivided** (Holocene and upper Pleistocene) – Mostly poorly sorted and poorly bedded sand, silt, and clay with some gravel; typically mapped where alluvium has been deposited on lacustrine deposits in intermontane depressions and Cache Valley; thickness uncertain.

Qac **Alluvium and colluvium, undivided** (Holocene to middle Pleistocene) – Undifferentiated stream and fan alluvium, colluvium, and, locally, mass-movement (landslide and slump, and talus) deposits too small to show separately at map scale; mostly gravelly deposits mapped in upper reaches of canyons and along drainages, where colluvium-covered hillsides grade imperceptibly into alluvium-filled valleys without distinct slope breaks; 0 to about 30 feet (0–9 m) thick.

Qadp **Alluvial-fan and deltaic deposits** (middle? Holocene and upper Pleistocene) – Clast-supported, mostly poorly bedded gravel with sand, silt, and clay matrix; locally containing equal amounts of gravel and sand, and locally cross-bedded; mapped at mouth of Wellsville Canyon upslope from an approximately located Provo shoreline (P); at least 60 feet (18 m) thick (could be 160 feet [50 m] thick) in well near Mount Sterling (NW1/4 section 15, T. 1 N., R. 1 W.) (after Utah Division of Water Rights website). Also deposited in fan-delta at mouth of Box Elder Canyon with upper surface more than 50 feet (>15 m) below top of adjacent Provo-shoreline delta (Qdp). A fan-delta is built when an alluvial fan enters a lake or ocean, and includes both the fan and the delta.

The fan-delta at Box Elder Canyon, in contrast to adjacent deltaic deposits, contains no calcareous cement, and clasts are subangular to well rounded and poorly to moderately sorted with deposits coarsening up slope and up drainage. Personius (1990) first noted that deposition at the mouth of Box Elder Canyon was a fan-delta, with 20 to 70 percent rounded recycled Lake Bonneville clasts, after the recession of Lake Bonneville from the Provo shoreline. At Box Elder Canyon, this map unit probably includes Provo-stillstand lacustrine-deltaic deposits, sub-Provo-stillstand alluvial-fan and lacustrine-deltaic deposits that contain abundant reworked materials from the Provo-shoreline delta, and locally overlying alluvial-fan deposits. In subsurface in the Brigham City quadrangle, Jensen and King (1996) reported the fan-delta is 125 feet (38 m) thick, with 45 feet (14 m) of underlying fine-grained Lake Bonneville deposits, probably including prodelta (bottom-set) deposits, and 240+ feet (73+ m) of pre-Lake Bonneville alluvial-fan gravel below the lacustrine deposits.

Historical (Human) Deposits

Qh **Human disturbance** (historical) – Primarily surficial materials and rock debris moved during sand and gravel operations, and highway, dam and dike construction; only those areas that obscure bedrock and natural deposits and are large enough to show at map scale are mapped; disturbances mapped include construction material pits east of Brigham City, roadbed beneath U.S. Highway 89, maintenance yards and historic paving plants along U.S. Highway 89, and dam/dikes at Mantua Reservoir; thickness unknown.

DESCRIPTION OF BEDROCK MAP UNITS

Tertiary

Tu, Tcg, Tts

Tertiary rocks, undivided (ages uncertain) – Conglomerate, tuffaceous sandstone and siltstone, freshwater limestone, altered tuff/claystone, and tuff (Tu = undivided, Tcg = conglomeratic, and Tts = tuffaceous); units only mapped in southeast part of map area near Paleozoic rocks where rocks could be of any Tertiary age, because of multiple Tertiary unconformities; so mapped where Pliocene and late Miocene Salt Lake Formation cannot be differentiated from unconformably underlying Oligocene and Eocene Norwood Formation and/or unconformably underlying Eocene Fowkes Formation equivalent strata; units unconformably overlie Wasatch and older formations.

King mapped most exposures on the east margin of the quadrangle as Norwood and Fowkes equivalent strata (Tnf, Tn?, and Tf? on map), while those "poking" through Lake Bonneville deposits in Cache Valley are Salt Lake Formation (shown as Ts on map). This means a fault with down-to-the north offset must be present between these two groups of exposures.

The unconformity between the Salt Lake Formation and underlying Norwood-Fowkes-equivalent strata is obscure unless this angular unconformity is lower or higher in the section (farther west or east, respectively) than shown by Smith and Oaks (1997) and Oaks and others (1999). King mapped the Salt Lake–Norwood (Ts-Tn?) contact farther to the east than their contact, but an angular unconformity is not visible on aerial photographs. The angular unconformity visible on aerial photographs farther to the west, below the Tfn-Tsl contact shown by Smith and Oaks (1997) and Oaks and others (1999), has been mapped as the Norwood(Tn?)-Fowkes(Tf?) contact in this report.

Ts, Tscg

Salt Lake Formation (Pliocene and late Miocene) – Conglomerate, tuffaceous sandstone and siltstone, freshwater limestone, altered tuff/claystone, and tuff; mostly mapped as undivided (Ts); conglomerate (Tscg) mapped locally.

Subdivided into several units with letter suffixes by Smith and Oaks (1997) and Oaks and others (1999). But, King considers their lower units (any below f) to be part of his Norwood and Fowkes units. In order of increasing uncertainty, King has mapped Ts, various Ql/Ts (Ql, Qla, Qlb, Qlsb, and Qlgb over Ts), and various Ql/Ts? (Ql, Qlb, Qlg, Qlgp, Qlgb, and Qlsb over Ts?) where what appears to be bedding in the Salt Lake Formation is visible on aerial photographs in the northeast (Cache Valley) part of the map area. Many of these outcrops (Ts) and subcrops (Ql--/Ts, Ql--/Ts?) were previously shown by Smith and Oaks (1997) and Oaks and others (1999), though outlines differ.

If the Salt Lake Formation in Cache Valley in the northeast part of the Mount Pisgah quadrangle has a uniform dip and no structural geologic complications, these strata could be about 3000 feet (900 m) thick (see Oaks and others, 1999, figure 7). Only the upper part of this interval is well exposed, east of the quadrangle near Hyrum Reservoir; these exposures include conglomerate and limestone as well as the more typical tuffaceous sandstone, siltstone and claystone, and tuff (see Smith, 1997; Oaks and others, 1999). Miocene (<10.5 Ma) ages reported in Smith (1997) and Oaks and others (1999) for tuffaceous fill in southern Cache Valley are based on chemical correlations of volcanic glass. These correlations are suspect because this glass is metastable and the chemical composition can change during wetting, hydration, and the change from ash to tuff (cementation/induration), even before the glass ceases to look like glass. Also glass chemistry varies during any eruption event. Therefore, these ages should be considered proxies until isotopic ages are obtained on Cache Valley tuffs. However, much of the tuff in the Salt Lake Formation likely came from late Miocene and Pliocene (<16 Ma) eruptive centers in the eastern Snake River Plain (see Perkins and others, 1998; Perkins and Nash, 2002; Anders and others, 2009). Long and others (2006) provided zircon U-Pb ages for one sample of tuffaceous sandstone that vary from 11 to 18 Ma, and also include older zircons (22 Ma, 34 Ma, 40 to 45 Ma [see Tnf] and 1600 to 1900 Ma [Farmington Canyon complex near Ogden], see Barnett and others, 1993).

Tnf, Tn?, Tf?

Norwood? and/or Fowkes? Formations (upper Oligocene and lower Eocene) – Conglomerate, tuffaceous sandstone and siltstone, freshwater limestone, altered tuff/claystone, and tuff; typically light gray to light brown; Norwood(Tn?)-Fowkes(Tf?) contact mapped at angular unconformity that is visible on aerial photographs. Oaks and others (1999) noted that their Salt Lake Formation is separated from their Fowkes-Norwood unit (Tfn) by a discontinuous conglomerate as well as an angular unconformity. However, their mapped contact/unconformity is obscure, having no angular discordance, so King mapped the contact to the west. The units are therefore queried due to the uncertainty of the Ts-Tn and Tn-Tf contact locations, as well as poor exposures, limited isotopic dating, and multiple Tertiary unconformities. Also, the age and stratigraphic relationships between the Norwood and Fowkes Formations have not been determined.

Oaks and others (1999) showed a Fowkes-Norwood unit (Tfn) on the east margin of the Mount Pisgah quadrangle and extending east into the Paradise quadrangle. Because Oaks and others (1999, figure 7) show at most 600 feet (180 m) of their Tfn unit, the site of 1410 feet (430 m) thickness reported in their text (Oaks and others, 1999, p. 86) is not known. Their unit seems to be the lower part of the tuff unit previously shown by Williams (1962) in the same area, with Oaks and others' (1999) lower Salt Lake Formation (units Tslc and Tsld) being the upper part of Williams' tuff unit. King thinks Williams' tuff unit is Norwood-Fowkes-equivalent strata and has shown it as such on the accompanying map. Including Oaks and others' (1999) Tsld lithosome (+650 feet) with their documented Tfn thickness (600 feet) would mean the Norwood-Fowkes-equivalent strata of this report (Williams' tuff unit) is more than 1250 feet (380 m) thick.

Williams (1962) showed his tuff unit as an irregular band adjacent to Paleozoic rocks on the boundary between the Mount Pisgah and Paradise quadrangles; he described it as 1200 feet (365 m) of earthy gray tuff, with two distinctive limestone beds near the base and a minor amount of pebble conglomerate. Williams (1962) described the lower limestone bed as about 10 feet (3 m) of light-colored, commonly siliceous, freshwater limestone that unconformably overlies Paleozoic rocks or Wasatch(?) redbeds, and the upper limestone as 1 to 2 feet (0.5 m) of gray, stromatolitic (oncolitic?) limestone that is separated from the basal limestone by a few feet of tuffaceous sandstone.

Smith (1997) placed these limestones in the Norwood-Fowkes strata (her unit Tfnx), likely due to the unconformity noted by Williams (1962), while Oaks and others (1999) placed the limestones in the Wasatch Formation (their unit Twx), based on oncolites like those in the Wasatch Formation in the Bear River Range (see Oaks and Runnells, 1992). Oaks and others (1999, figure 7) showed the limestone unit as about 50 to 100 feet (15–30 m) thick. King has placed the upper Wasatch contact at the upper edge of reddish strata (see Tw? below), west of (below) their limestone units (Tfnx and Twx, respectively); this was done for several reasons in addition to the color change. Their limestone unit is not always visible on aerial photographs, and on the ground the limestones are thin (like Williams [1962] described) and discontinuous, and their map unit appears to King to typically be a poorly exposed marly interval above the Wasatch Formation. Therefore, their unit may not be a reliable marker. Further, the unconformity that should be between the Wasatch Formation and overlying strata is not distinct at either the top or bottom of the marly interval and Williams (1948, p. 1146) reported a tuff lens in the Wasatch Formation in the Bear River Range.

K-Ar isotopic ages from near the base of the Tf? unit along Baxter Ridge (see map) are 44.2 ± 1.7 and 48.6 ± 1.3 Ma on hornblende and biotite, respectively (table 1). Hornblende typically "sets" earlier than biotite, so age inversion here implies reworking of tuff prior to deposition (two separate air-fall events) or K-Ar disequilibrium/alteration of one of the minerals (biotite typically alters more easily than hornblende). These ages are older than Norwood and Fowkes ages in Utah, and are more like older Fowkes Formation ages in Wyoming. Norwood has been K-Ar isotopically dated at 38.4 Ma (sanidine, corrected) in the type area to the south near Morgan, Utah (see Evernden and others, 1964) and 39.3 Ma (biotite, corrected) from farther south in East Canyon (Mann, 1974). Greenish altered tuff in the basal Fowkes (Bulldog Member) has been $^{40}Ar/^{39}Ar$ isotopically dated at 40.41 Ma and 38.78 Ma on biotite and hornblende, respectively, in the Castle Rock quadrangle, Utah (center NW1/4, section 35, T. 4 N., R. 7 E.; center SE1/4, section 27, T. 4 N., R. 7 E.; respectively); again note age inversion. Older Fowkes ages in Wyoming are: 1) 47.94 ± 0.17 Ma ($^{40}Ar/^{39}Ar$, sanidine) at the northeast end of the Crawford Mountains (Smith and others, 2008, p. 67), south of the Fowkes type area (see Oriel and Tracey, 1970); 2) 49.1 Ma (K-Ar, biotite; recalculated from 47.9 ± 1.9 Ma in Nelson, 1979; analyzed in 1977, but decay constant not reported, so may not need to be recalculated), likely from near the base of the Fowkes (NE1/4 NE1/4 sec. 2) in the Murphy Ridge quadrangle in Wyoming (Nelson, 1973 – NE1/4 sec. 2, T. 15 N., R. 121 W.); and 3) 48.9 Ma (K-Ar, hornblende; recalculated) from the Fowkes type area to the north in Wyoming (47.7 ± 1.5 Ma in Oriel and Tracey, 1970).

Oaks and others (1999) also reported a much older (64 Ma) K-Ar hornblende age for the Cache Valley fill along the Little Bear River to the east in the Paradise quadrangle. This age is now suspect because the sample submitted with it was isotopically dated at about 32 Ma, not much different from the 30 Ma that Oak and others (1999) reported from a nearby sample via chemical correlation; so the samples may have been switched. In addition, Yonkee and Weil (2011, figure 7) show a lower Paleocene (~58–64 Ma) gap in uplift of the Wasatch anticlinorium, the source of Eocene to Cretaceous basin fill in the area. However, Williams (1964) reported K-Ar ages on mineral separates from Cache Valley fill of 55 to 70 Ma (corrected), though with large errors (±6–10 Ma). If these Paleocene to Cretaceous ages are correct they may indicate recycled hornblende in younger rocks, or uncommon Paleocene to Cretaceous deposition in a piggy back basin like the later (and farther east) Wasatch Formation piggy back basins with oncolitic limestones (see Coogan, 1992).

Tw, Tw?

Wasatch Formation (Eocene-upper Paleocene) – As mapped on the east margin of the quadrangle, unit is typically red, conglomeratic mudstone and locally white-weathering, gray, oncolitic limestone, with reddish to yellowish sandstone and siltstone and light-gray marlstone; conglomerate is poorly exposed with clasts typically seen as float on reddish to brownish muddy slopes; other lithologies are also poorly exposed; oncolitic limestone is visible only as oncolite float and, as shown on map, does not cap the Wasatch Formation; Wasatch strata likely up to 200 feet (60 m) thick (see Smith, 1997), though King seldom saw more than 40 feet (12 m) of reddish strata exposed; unconformably overlies Oquirrh Formation that has considerable paleotopography; regionally the Wasatch Formation is Eocene and upper Paleocene (Nichols and Bryant, 1990); in map area underlies strata isotopically dated as Eocene (see Tnf, Tf? above); Paleocene and Cretaceous K-Ar ages reported by Williams (1964) for rocks unconformably overlying the Oquirrh Formation in southern Cache Valley are suspect due to large error margins on mineral separates, suggesting ages are inaccurate or are averages of several air-fall events (that is, deposits are reworked and could be younger than Cretaceous).

Previously, Williams (1962) had tentatively correlated soft red sandstone, located below his Salt Lake Formation limestone on the west margin of the Paradise quadrangle (NE1/4 sec. 6 and NE1/4 sec. 7, T. 9 N., R. 1 E.), with the Wasatch Formation, but he did not map the extent of either unit. Mullens and Izett (1964) did not mention redbeds in their work on the Paradise quadrangle. Smith and Oaks (1997) and Oaks and others (1999) show basal Wasatch outcrops (their Tw below limestone unit) as more extensive than King mapped them in this report, because their basal Wasatch strata locally appear to King to be reddish residuum and colluvium from the Oquirrh Formation and part of unit Qafo.

Origin and age of red deposits are uncertain in the map area, and for several reasons might be variable. Some exposures are red-stained conglomeratic strata similar to what Goessel (1999) mapped as Wasatch Formation in the northern Wellsville Mountains; in contrast Oviatt (1986) chose to not call similar red-stained rocks Wasatch Formation, implying the stain was in younger rocks that inherited the red from erosion of the Wasatch. Further, the extent of the Wasatch Formation in the Mount Pisgah area is difficult to determine. Only reddish strata (not unlithified, unbedded deposits) are shown as Wasatch Formation (Tw) on map. Other non-red conglomerates might be Wasatch Formation, but they could be part of other units, and unconsolidated reddish deposits likely have multiple origins. The Wasatch Formation may be present in the subsurface in a well at Mount Sterling (NE1/4 section 15, T. 10 N., R. 1 W.), because a red limestone is reported at a depth of 187 feet (m) and this limestone overlies red gravel (both likely Wasatch), and then at 250 feet, probable Oquirrh Formation (after Utah Division of Water Rights website).

These uncertainties are the reason for the query on the unit label (Tw?) in parts of the quadrangle. For example, queried Wasatch (Tw?) strata near Dry Canyon and in section 30, T. 10 N., R. 1 E. are red-stained material. The Dry Canyon locale is in a depression and might be terra rossa (see following notes on second uncertainty) or Pleistocene alluvial fans (Qafo). The two locales in section 30 are very poorly exposed, thinner than Tw to the north, next to red-weathering Oquirrh Formation, and are partially covered by (or part of) unit Qafo; without the exposure of Wasatch and angular unconformably overlying Tf? in Big Spring Hollow east of the map area, these two locales would not have been mapped as Tw? by King.

First uncertainty – Locally derived Wasatch conglomerates are not necessarily red. The lack of red color in the strata that onlap the Oquirrh Formation south of Big Spring Hollow mean they have been mapped as unconformable onlap of the Fowkes unit (Tf?) onto considerable paleotopography, but the Tf? unit might actually be a local (non-red) Wasatch unit (see below), or might even be Cretaceous and/or Paleocene in age like the Evanston Formation (see Tnf discussion above).

Second uncertainty – The clast composition in the basal conglomerates (Tw, Tw?, Tf?, and Tcg of this report) does not help with identification because the clasts are predominantly angular to subangular cobbles of Oquirrh Formation (compare data and locations in Smith, 1997, to our map) that imply a nearby source in the Pisgah Hills. Oaks and others (1999) reported angular to subangular cobbles of Eureka (Swan Peak) quartzite, but King has not observed these distinct clasts. Swan Peak clasts are reported on erosion surfaces on Clarkston Mountain (Biek and others, 2003) and the north end of the Wellsville Mountains (Goessel, 1999). It has been assumed these surfaces formed in the latest Tertiary (Pliocene) to early Quaternary (QT), but Williams (1948) suggested the Rendevous Peak surface (type area adjacent to Mount Pisgah quadrangle) formed after Cache Valley began to form and before the Salt Lake Formation was deposited, but later (Williams, 1958, p. 15) revised this to post Salt Lake Formation. These mostly Oquirrh clasts are typical of local basal Wasatch Formation in that they lack rounded Precambrian and Cambrian quartzite clasts. These local conglomerates also typically lack rounding and the strong red-colored matrix that are typical of quartzite-clast Wasatch conglomerates, leaving doubt that they are Wasatch Formation strata (see for example Coogan and King, 2006; King and others, 2008). Alternatively, rather than being Wasatch strata, the local conglomerates are some younger conglomerate like those seen interbedded with and unconformably overlying the Norwood Formation in the Durst Mountain quadrangle (see Coogan and King, 2006).

Third uncertainty – Unconsolidated reddish units could be from weathering, karst dissolution, or erosion of red Wasatch strata. In the map area, the Oquirrh Formation, which unconformably underlies the Wasatch, typically weathers to reddish residual and colluvial material, and reddish residual material (terra rossa) was produced during karst development in the area, and is particularly noticeable in depressions. Note that in water wells in sections 22 and 23 (T. 10 N., R. 1 W.) red shales(?) are intercalated with brown, medium-gray, and black fractured limestone, which seems to indicate terra rossa (and cavern fill?) preserved in the subsurface; red gravel (Wasatch or some younger gravelly unit) overlies the intercalated materials in two wells (after Utah Division of Water Rights website). As noted under unit Qafo, reddish gravels and conglomerate(?) are present in the subsurface near Wellsville (section 10, T. 10 N., R. 1 W.) (after Utah Division of Water Rights website) and could be part of the Wasatch Formation and/or some younger units (Tertiary conglomerates and/or Quaternary alluvial deposits) derived from (reddened by) the Wasatch Formation.

Fourth uncertainty – South of the Pisgah Hills in the Mantua and James Peak quadrangle, reddish gravels on flats, mapped as Tb by Ezell (1953), likely have yet another origin and similar deposits in the Mount Pisgah quadrangle could have the same origin. Crittenden and Sorensen (1985) mapped these deposits as undivided Evanston and Wasatch Formations (TKwe), despite noting that the deposits might be lags and are unconsolidated. These gravels have not been recognized in the Mount Pisgah quadrangle during the present mapping. Crittenden and Sorensen (1985) described these deposits as reddish-brown weathering, cobble and boulder "conglomerate" (actually unconsolidated, so are gravels), with clasts that are mainly tan, greenish, and purple quartzite derived from Geertsen Canyon (tan) and upper Proterozoic quartzite bedrock (green=?Papoose Creek and purple=?Mutual). The deposits are on flats and boulder-covered slopes and may be lag deposits (after Ezell, 1953; Crittenden and Sorensen, 1985). These gravels are mapped like colluvium and lag on hill slopes and tops, respectively, at elevations of about 6500 to 7360 feet (1980–2245 m) and appear 40 to 60 feet (12–18 m) thick on the erosional(?) surface near Rendevous Peak (up to 7360 feet [2245 m] elevation on "peak" east of Sink Hole valley that is unnamed on Mantua topographic map). The much greater 0- to 245-foot (0–75 m) thickness reported by Crittenden and Sorensen (1985) seems to be the product of slopewash and creep; that is colluvial boulders have moved downhill from hill-top surfaces. Ezell (1953) noted that these boulder deposits are on the Rendevous Peak erosional surface, and, following Williams (1948), the surface age was between the start of Cache Valley forming and Salt Lake Formation fill in this valley. This would place deposition of the surface-mantling and basal, reddish-brown gravel/conglomerates and surface formation between the start of Eocene-Oligocene relaxation and before mid-Miocene Basin and Range normal faulting. Coogan (1999, unpublished) mapped unit Tb of Ezell (1953) as a conglomerate in the Salt Lake Formation, and a Pliocene angular unconformity is present in the Salt Lake Formation in northwestern Utah (David M. Miller, U.S. Geological Survey, manuscript).

Pennsylvanian

IPo **Oquirrh Formation, upper** (Virgilian through Desmoinesian, Atokan?) – Gray, variably calcareous sandstone with interbedded sandy limestone and limestone; weathers to rubble-covered outcrops of light-brown to yellow-brown to orange-brown sandstone and light-brown to light-gray limestone; regularity of bedding thickness distinctive; forms ridges in Pisgah Hills and rubbly slopes in Wellsville Mountains; fusulinids common in some lower beds in Honeyville quadrangle; about 5000 feet (1525 m) thick, including basal West Canyon Limestone (after Oviatt, 1986).

Oviatt (1986, table 1) reported numerous fusulinids/foraminifera (for example, *Wedekindellina* sp. and *Eowaeringella* sp. – Desmoinesian and Missourian in age, respectively) and a few coral (*Neosyringopora* sp. – Virgillian?) from the lower part of the Oquirrh, above the West Canyon, in the Wellsville Mountains. Williams (1943, and Williams and Yolton, 1945) reported numerous brachiopods, bryozoans and ostracods, some horn and tabulate coral, one gastropod, and fusulinids from the lower part of his Wells Formation (Oquirrh) in the northern Wellsville Mountains. Beus (1958) and Gelnett (1958) reported fusulinids of Desmoinesian to Virgilian (Pennsylvanian) age in roughly the lower third of the unit; see also Nygreen (1955, 1958), although his Sardine Canyon measured sections are poorly located and potentially cut by faults. Oviatt (1986, table 1) also reported that a cobble in Tertiary conglomerate at the north end of the Wellsville Mountains contained Early Permian fusulinids (*Schwagerina* sp.), but in-place Permian strata reported by Bissell (1962) have not been confirmed.

IPow **West Canyon Limestone Member, Oquirrh Formation** (Morrowan) – To the northwest in the Honeyville quadrangle, West Canyon strata are about 400 feet (120 m) of interbedded cherty limestone, calcareous sandstone, and sandy limestone with *Idiognathodus sinuosis* zone conodonts (middle Morrowan) (Oviatt, 1986); not as easily mappable in this quadrangle because the basal Oquirrh Formation is typically a calcareous sandstone (see for example Williams and Yolton, 1945) rather than a limestone; contact with overlying Oquirrh strata placed where rocks become less resistant, making unit about 400 to 800 feet thick (120–240 m) on map.

Mississippian

Mmc **Manning Canyon Shale** (Chesterian) – Interbedded gray, silty, thin-bedded, cherty limestone and calcareous siltstone and some olive-gray to black shale; fossiliferous, numerous brachiopods and pelecypods, some inarticulate brachiopods, gastropods and sponges, and a cephalopod and horn coral reported by Williams and Yolton (1945, unit 5); variably resistant as slope and ridge former in Pisgah Hills; poorly exposed scree slopes in Rattlesnake Canyon, Wellsville Mountains; an estimated 900 feet (270 m) total thickness in Rattlesnake Canyon (see Jensen and King, 1996); reported thickness at Dry Lake measured section is 950 feet (290 m) (Brazer 5 of Williams and Yolton, 1945) (see also figure 2); thins south of Dry Lake to an estimated 600 feet (180 m) thick. Near Dry Lake, the Manning Canyon (Brazer unit 5) was assigned a Chesterian age, based on brachiopod fossils (*Rhipidomella nevadensis*, *Spirifer brazerianus*), by Williams and Yolton (1945); see also Yolton (1943) and Sadlick (1955, p. 75–77). Miller and others (1991) reported a Mississippian and Pennsylvanian age for the Manning Canyon to the west in the Blue Spring Hills (Lampo Junction quadrangle), but their upper Manning Canyon might be equivalent to the West Canyon Limestone in the Wellsville Mountains (Jensen and King, 1996).

Sadlick's (1955) reported thickness at Dry Lake (1130 feet [344.4 m]) was measured across a fault and he probably used different contacts than those of this report. Therefore, his Manning Canyon thickness cannot be used for comparison; the Manning Canyon in this report is probably his unit 18 and below. Note also that his unit 16 is about 45 feet (15 m) of cover and might be a fault. Dutro (1979) also used different Manning Canyon and Great Blue Limestone member contacts than those of this report.

Mgb **Great Blue Limestone, undivided** (Chesterian and Meramecian) – Used southeast of Sardine Summit, where members are not distinct; there the middle member becomes more resistant possibly due to less shale. In map area on east slope of Wellsville Mountains, all members form scree-covered slopes such that descriptions are from the Pisgah Hills. The Great Blue Formation is Meramecian and Chesterian (middle to late Mississippian) in age from fossils collected in the Pisgah Hills and Wellsville Mountains (Williams, 1943; Yolton, 1943; Williams and Yolton, 1945, Brazer units 2–4; Sando and Bamber, 1985; Oviatt, 1986). Additional details on the Great Blue in the Wellsville Mountains and Pisgah Hills are provided in Lindsay (1977) and Sweide (1977), and without benefit of site specific data by Butkus (1975). However, Lindsay's (1977) Great Blue includes parts of the Little Flat (Humbug) and Oquirrh Formations of this and previous reports (Williams, 1948, 1958; Beus, 1958; Gelnett, 1958; Oviatt, 1986) on the Wellsville Mountains. Also, Sweide's (1977, figures 3, 5, and 9) contacts do not appear to be those of Williams and Yolton (1945, figure 2) or those used on our map. For example, Sweide (1977, p. 19) noted that Williams (1948) placed the shale bed with *Rugosochonetes* and *Orthotetes* in Brazer unit 5 (our Manning Canyon Shale), though Williams (1948, 1958) did not map contacts of the Brazer (Great Blue equivalent) units.

Mgu **Upper member** – Dark-gray, cherty, ledge- and ridge-forming limestone; fossiliferous, containing silicified brachiopods, crinoid stems, and horn, rugose, and tabulate corals (*Siphonophyllia* sp., coral zone V of Sando and Bamber, 1985) in the Wellsville Mountains (Jensen and King, 1996; see also site 20 of Oviatt, 1986) and Pisgah Hills (unit 4 of Williams and Yolton, 1945); 740 feet (225 m) thick. Reportedly 950 feet (290 m) thick at Dry Lake measured section (Brazer 4 of Williams, 1943, and Williams and Yolton, 1945), but lower 200 feet (60 m) may be part of middle member (Brazer 3); thins to south of Dry Lake.

Mgm **Middle member** – Interbedded, olive-gray mudstone and shale, and gray limestone, that form brownish slopes and gray to dark-gray ledges, respectively; mudstone contains micrite nodules; thinner bedded and overall less resistant than upper and lower members; about 600 feet (180 m) thick, thinning to south to about 300 feet (90 m), and may thin to absence to south or become more resistant with pinching out of shale; queried where more resistant, and upper and/or lower contacts uncertain; reportedly 470 (or 670) feet (145 or 205 m) thick at Dry Lake measured section (Brazer 3 of Williams and Yolton, 1945; see also Williams, 1943), but contact with upper member may not be placed correctly. Top of middle member likely contains *Cavusgnathus* sp. conodonts (site 19 in upper member of Oviatt, 1986); Williams and Yolton (1945) also reported fossil pelecypods, brachiopods, echinoderms, an inarticulate brachiopod, a cephalopod, and one or two gastropods.

Mgl **Lower member** – Medium- to dark-gray, ridge-, ledge-, and slope-forming limestone; fossiliferous, containing age-diagnostic *Faberophyllum* sp. and *Siphonodendron* (*Lithostrotion whitneyi*) corals indicating coral zones IV and IIID, respectively (Oviatt, 1986; see also Sando and Bamber, 1985), *Cavusgnathus* sp. conodonts (Oviatt, 1986), and *Goniatites* sp. and *Girtyoceras* sp. cephalopods (Williams and Yolton, 1945), as well as fossil sponges, echinoderms, brachiopods and gastropods, other cephalopods, and other tabulate, rugose, and horn corals (see Williams and Yolton, 1945); about 800 feet (240 m) thick; reportedly only 400 feet (120 m) thick (Brazer 2) at Dry Lake measured section (see Williams, 1943; Williams and Yolton, 1945), indicating problems with their measured section.

Mlf **Little Flat Formation** (Merimecian and Osagean) – Gray, tan, and reddish-tan, brown-weathering, calcareous sandstone with sandy limestone and dolomite; grades upward into mostly dolomite; less resistant than overlying and underlying map units; about 900 feet (270 m) thick including Delle Phosphatic Member. Delle Phosphatic Member is resistant, cherty limestone, with underlying less resistant, calcareous sandstone and dark phosphatic shale; weathers distinctive orange brown and locally mappable (Mlfd); about 90 feet (27 m) thick. Little Flat is equivalent to Brazer 1 of Williams (1943, 1948); see also Williams and Yolton (1945) for fossils, mostly brachiopods (*Cleiothryidina obmaxima* – likely coral zone IIID) and some corals. In the Bear River Range, the Little Flat is early Osagean to middle Meramecian (Early and Late Mississippian) in age, based on conodonts, and is approximately time-equivalent to the Deseret Limestone (Sandberg and Gutschick, 1979).

The Little Flat Formation is equivalent to rocks in the Honeyville quadrangle that Oviatt (1986) mapped and labeled Deseret Limestone and Humbug Formation (figure 2). From *Ekvasophyllum* sp. and *Canadiphyllum* sp. coral he collected (Oviatt, 1986, table 1), Oviatt's (1986) Humbug is at least Meramecian in age (likely coral zone IIID of Sando and Bamber, 1985). We called these rocks Little Flat because they are lithologically similar to the type Little Flat Formation in the Chesterfield Range in southeastern Idaho (W.J. Sando, U.S. Geological Survey, written communication, 1988; see Dutro and Sando, 1963, for type descriptions). Gelnett (1958) and Beus (1958) did not recognize phosphatic rocks in the Wellsville Mountains and placed about 90 feet (27 m) of thin-bedded, black, chert-bearing limestone (in Deseret of Oviatt, 1986) in their uppermost Lodgepole Limestone (figure 2).

Ml **Lodgepole Limestone** (Osagean? and Kinderhookian) – Gray, typically cherty limestone that forms steep slopes and ridges in Pisgah Hills; contains black chert nodules, particularly at top; about 1000 feet (300 m) thick; fossiliferous, in Brigham City quadrangle contains crinoid, coral, brachiopod, bryozoan, and some branch-like fossils (Jensen and King, 1996). Based on fossil conodonts (upper and lower *Siphonodella isostichia – S. crenulata* zones), crinoids, and corals, and depending on the Kinderhookian-Osagean boundary relative to the lower boundary of the *Gnathodus typicus* conodont zone, the Lodgepole is Kinderhookian and possibly early Osagean (Early Mississippian) in age in northern Utah and the Wellsville Mountains (Sandberg and Gutschick, 1979; Oviatt, 1986; respectively). Unconformably overlies Lower Devonian Water Canyon Formation in Mount Pisgah quadrangle; Middle and Upper Devonian Hyrum Dolomite and overlying Beirdneau Sandstone are present in adjacent quadrangles (see figure 2; Crittenden and Sorensen, 1985; Oviatt, 1986; Jensen and King, 1996; Coogan and King, 2016).

A recess is not present between the Lodgepole Limestone and unconformably underlying Devonian rocks in the Pisgah Hills (Williams, 1948). Regionally, this recess includes the Cottonwood Canyon Member of the Lodgepole Limestone of Sandberg and Gutschick (1979) and/or the Leatham Formation. The Cottonwood Canyon Member (Mississippian, Kinderhookian) is shale and thin-bedded limestone that is 10 to 30 feet (3–9 m) thick less than 10 miles (16 km) to the east in the Logan Peak syncline (see shales of Williams, 1948; Holland, 1952; Benson, 1965) (see also Sandberg and Gutschick, 1979). The Leatham Formation (Upper Devonian, Famennian) is dark-colored shale, siltstone, and limestone that is 15 to 100 feet (4.7–30 m) thick to the east in the Logan Peak syncline (Holland, 1952; Sandberg and Gutschick, 1979; Coogan and King, 2016; also after Brooks, 1954; Mullens and Izett, 1964). Where a Kinderhookian age is reported for the Leatham, it is considered an indication that the Cottonwood Canyon Member is present.

Devonian

Water Canyon Formation – White and orange stripes of this unit are easily traceable on ground and aerial photographs, though exact contacts are difficult to map because members are easily eroded and resulting detritus mantles underlying units; overall argillaceous, thin to medium bedded, and poorly exposed. The Water Canyon is Lower Devonian based on fish fossils found in the Wellsville Mountains (Oviatt, 1986) and in northern Utah (Taylor, 1963; Williams and Taylor, 1964). Subdivided into three members in this quadrangle.

Dwu **Upper member** – Light-gray- to white-weathering, light-gray to light-tannish-gray dolomite and some limestone; locally sandy; 450 feet (140 m) thick. Should pinch out to south in map area, since reportedly very thin or absent in northeast Mantua quadrangle (Crittenden and Sorensen, 1985), but does not appear to thin in Mount Pisgah quadrangle.

Dwm **Middle member** – Grayish-yellow, fine-grained sandstone to siltstone and interbedded sandy dolomite and limestone; typically orange-brown weathering and slope forming; 400 feet (120 m) thick. Our middle map unit includes parts of both Water Canyon members of Williams and Taylor (1964) at their reference section near Honeyville (figure 2), but Williams and Taylor (1964) apparently used the Water Canyon–Laketown contact of Beus (1958) and Gelnett (1958) (see below).

Dwl **Lower member** – Light-gray weathering, ledge- and slope-forming, relatively thin-bedded dolomite; locally sandy; about 400 feet (120 m) thick. Reportedly disconformably overlies Laketown Dolomite (Taylor, 1963; Williams and Taylor, 1964), but unconformity not noticeable in the field. Oviatt (1986) equated the lower map unit with the type Card Member of Williams and Taylor (1964); however, see figure 2 in this report. Beus (1958) and Gelnett (1958) measured about 370 to 410 feet (113–125 m) of strata that are comparable to the lower member, but they placed this strata in the Laketown Dolomite (figure 2). The lower map unit is lighter in color and less resistant than the underlying Laketown Dolomite, and contains detrital material. A change to thinner beds in the lower map unit, compared to the Laketown, has been widely reported but is not present everywhere (Jensen and King, 1996).

Silurian and Ordovician

SO **Laketown and Fish Haven Dolomites, undivided** – In the Pisgah Hills these dolomites are incompletely exposed and faulted, making division impractical; these dolomite units are locally mapped separately, but even then the contact is uncertain because Fish Haven weathering resistance is typically no different than overlying Laketown.

Sl **Laketown Dolomite** – Medium- to dark-gray, medium- to very thick bedded, ridge-forming dolomite, with irregular blebs, stringers, and layers of chert at various horizons; locally interlayered light and dark color in lower part; likely about 1100 to 1200 feet (335–365 m) thick (after Gelnett, 1958; Gunn, 1965; see also Oviatt, 1986). In a measured section east of Mantua Reservoir, probably in the Mount Pisgah quadrangle, Gunn (1965, p. 205) reported the Laketown was 973 feet (300 m) thick, and using our Laketown-Fish Haven contact, units 3 and 2 of his Fish Haven (30 and 66 feet [9 and 20 m] thick) would be in our Laketown (totaling 1072 feet [327 m] thick), leaving 166 feet (50 m) of Fish Haven (his unit 1 of Fish Haven). Using the Fish Haven–Laketown contact in the Brigham City quadrangle, the Laketown is late Late Ordovician and middle Early through Middle Silurian in age, and locally earliest Late Silurian in age in northern Utah (after Budge, 1966, 1972; Budge and Sheehan, 1980; Leatham, 1985). The biostratigraphic Laketown–Fish Haven contact of Budge (1972), Budge and Sheehan (1980), and Leatham (1985) is not mappable. Budge (1966) measured a Laketown section in the northeast Mantua quadrangle, but our Laketown–Fish Haven contact is likely in one of several covered intervals in his 278-foot (85 m) thick member A, that is, higher than his contact.

Ofh **Fish Haven Dolomite** – Very dark-gray-weathering, ridge-forming dolomite; likely about 180 feet (55 m) thick (after Jensen and King, 1996) using the contact that Williams (1948, 1958) probably mapped in the Bear River Range; contact typically mapped at top of darker dolomite where overlying Laketown is less resistant; unconformably overlies the Swan Peak Formation. Contains abundant fossil corals, particularly rugose corals, and tabulate (for example *Halysites* species) corals. Based on fossil corals collected in north-central Utah, the age of our Fish Haven map unit is probably late Late Ordovician (Cincinnatian, possibly Richmondian) (after Williams, 1948; *Paleofavocities* sp., Gelnett, 1958; Budge, 1972). Budge and Sheehan (1980) presented more detailed data, but they used a different Fish Haven–Laketown contact.

Ordovician

Osp **Swan Peak Formation** – Quartzite, shale to siltstone, and limestone, with distinctive capping, pale-orange, cliff- and ridge-forming quartzite; quartzite underlain by recessive-weathering interbedded dark shale to siltstone, similar quartzite, and limestone; 245 to 300 feet (75 to 90 m) thick, with roughly 60-foot- (18 m) thick capping quartzite in the Brigham City (Jensen and King, 1996) and Mount Pisgah quadrangles (after Ross, 1951); Francis' (1972) measured sections in the map area are incomplete, but his sections near Mantua indicate the Swan Peak thins to the south to about 200 feet (60 m) and then 100 feet (30 m) thick outside the map area, with the capping quartzite "cut out"; Ezell (1953) indicated the Swan Peak is mostly shale and only 50 feet (15 m) thick to the east near Rendezvous Peak in the James Peak quadrangle. The lower Swan Peak is late Early Ordovician in age based on Zone M (*Orthoambonites-Orthidiella*) fossil brachiopods and trilobites found in the Pisgah Hills and Wellsville Mountains (Ross, 1951; Gelnett, 1958, p. 28; Francis, 1972, p. 111 and 118; Jensen and King, 1996, table 2). Francis (1972) and Oaks and others (1977) provided details on the Swan Peak and its divisions, typically three thin units.

Ogc **Garden City Formation** – Gray- to tan-weathering, ledge-forming limestone; contains some intraformational flat-pebble conglomerate in lower half; contains tan- to yellowish-weathering, less resistant, wavy silt partings and is locally argillaceous; chert is common in lowermost part and near the top of unit (black nodules and stringers); above upper cherty zone Garden City is dark-gray dolomite and dolomitic limestone; lower part contains more abundant less-resistant partings/layers up to 1 inch (2.5 cm) thick of calcareous siltstone, sandstone, and shale (after Jensen and King, 1996); 1330 to 1390 feet (405–425 m) thick in Wellsville Mountains (Ross, 1951; Oviatt, 1986; Morgan, 1988). In map area and Brigham City quadrangle, contact with underlying St. Charles is difficult to locate; contact placed where both units are less resistant. The Garden City is Early Ordovician in age as determined from its rich Zone L to B fossil trilobite fauna in the Pisgah Hills and a *Buttsoceras* sp. fossil cephalopod in the Wellsville Mountains, and disconformably overlies the St. Charles Formation (Ross, 1951; Oviatt, 1986; see also Taylor and others, 1981). Morgan (1988) reported additional information on the petrology and origin of the Garden City Formation; 1389 feet (423 m) thickness measured in Mount Pisgah quadrangle (Ross, 1951) with 1406 feet (429 m) thick composite section (Morgan, 1988).

Cambrian

Csn **St. Charles and Nounan Formations, undivided** – Only mapped in possible landslide block.

Csc **St. Charles Formation** – Upper part is gray- to tan-weathering, typically ledge-forming dolomite; contains laminae to inch-scale layers of sandstone and siltstone that weather to tan mottled surfaces and recesses; uppermost part contains light-colored, typically pink, chert; as determined from trilobite and conodont fossils in the Bear River Range, the St. Charles Formation is Late Cambrian and earliest Ordovician in age (Taylor and others, 1981); total thickness about 950 feet (290 m).

Locally mappable lower unit (Csl) has Worm Creek Quartzite Member at base, with overlying tan- and gray-weathering, slope-forming, thin-bedded, silty and sandy limestone that is more like underlying carbonates in the Worm Creek than overlying carbonates in the St. Charles; *Elvinia* zone trilobite fossils in the Wellsville Mountains indicate a Late Cambrian age for the Worm Creek (Oviatt, 1986); lower unit about 170 feet (50 m) thick (after Maxey, 1941; Jensen and King, 1996).

Worm Creek Member not consistently defined (in some studies is quartzite with limestone and clastic-rich beds rather than just quartzite) and quartzite not present everywhere in northern Utah (see for examples Ezell, 1953, and Haynie, 1957, versus Hafen, 1961). This has led to problems with the presence or absence of the member as well as thickness, lithology, and member name (no lithology or quartzite in name). In the Brigham City quadrangle, the Worm Creek was defined as a basal 0- to 6-feet- (0 to 1.8 m) thick, light-gray to white quartzite with about 70 feet (21 m) of thin-bedded, silty to sandy dolomite and limestone, and siltstone and shale (Maxey, 1941; see also Jensen and King, 1996); but it is the lower unit, noted above, that is at least locally mappable. Because the bottom of the St. Charles and top of the Nounan Formation are typically limestone, the St. Charles contact with the conformably underlying Nounan can be difficult to distinguish where the basal quartzite is absent.

Cn **Nounan Formation** – Interbedded, very thick- to thick-bedded, light- to dark-gray- to tan-weathering interbedded dolomite, sandy and silty dolomite, and limestone, with partings (crude laminae and mottling) of sand and silt that weather tan; more sand and silt near the top and middle, with little sand and silt in more resistant lower part; typically forms cliffs, but only forms steep slopes in this quadrangle; about 1200 feet (365 m) thick (after Jensen and King, 1996). The Nounan cannot be subdivided into mappable units in this quadrangle. Williams (1948) reported that the Nounan was Late Cambrian in age, using unpublished fossil collections (in part from Maxey, 1941). Oviatt (1986) reported the upper Nounan was Dresbachian (Late Cambrian) in age based on *Dunderbergia*(?) and *Crepicephalus* zone trilobite fossil fauna. Gardiner (1974) and Maxey (1941) provided additional details on the formation in the Wellsville Mountains.

Bloomington Formation – Olive to tan shale and gray limestone; best exposed in quadrangle near Mantua, but overall poorly exposed. Maxey (1958) measured and described this unit where better exposed near Calls Fort Canyon in the Brigham City quadrangle. We placed the thin-bedded limestone that caps the Calls Fort Shale in the shale because it is more similar to the limestones in the Bloomington Formation than to the conformably overlying Nounan Formation dolomite. Based on trilobite and brachiopod fossil data from the Wellsville Mountains, the Bloomington shale members are Middle Cambrian (*Bolaspidella* zone) in age (Oviatt, 1986; Jensen and King, 1996, table 2). Subdivided into three members in this quadrangle.

Cbc **Calls Fort Shale Member** – Brown-weathering, slope-forming, olive-gray to tan-gray, thin-bedded shale to argillite with some interbedded thin-bedded, gray, silty limestone; limestone contains irregularly interbedded and intermingled partings to thin beds and masses of siltstone and shale that are more resistant than the limestone; in the Brigham City quadrangle, shale contains distinctive, 1- to 2-inch (2.5 to 5 cm) long, limestone nodules that weather out, leaving holes in the shales and littering gentle slopes (Jensen and King, 1996); about 235 feet (70 m) thick (after Maxey, 1958).

Cbm **Middle limestone member** – Gray, ridge-forming, argillaceous limestone with tan-, yellow-, and red-weathering, wavy, silty layers and partings, and minor thin beds of olive-gray and tan-gray shale and/or argillite; limestone is thick bedded at base and gradually becomes thin bedded at top; member typically forms “rib” between less resistant shale members; 515 feet (157 m) thick (Maxey, 1958).

Cbh **Hodges Shale Member** – Brown-weathering, slope-forming, olive-gray to tan-gray, thin-bedded shale to argillite with thin interbeds of gray, silty limestone; limestone contains irregular silty partings and layers like those in the middle limestone; fossiliferous, *Bolaspidella* trilobite zone; 335 feet (102 m) thick (Maxey, 1958).

Cbk **Blacksmith Formation** – Light- to medium-gray weathering, ridge-forming, typically medium-gray, very thick- to thick-bedded dolomite and dolomitic limestone; like other Cambrian carbonates contains tan-weathering, irregular, silty partings to layers; best exposed in quadrangle near Mantua; about 800 feet (245 m) thick. The fossil-poor Blacksmith is Middle Cambrian in age based on its position between two Middle Cambrian units whose ages are based on fossils (Maxey, 1958). Hay (1982) provided additional details on the lithology and origin of the Blacksmith in the Wellsville Mountains.

Cul **Ute and Langston Formations, undivided** – Locally mapped in fault blocks where formations not separable. Also contact between units is difficult to map.

Cu **Ute Formation** – Interbedded gray limestone and olive-gray to tan-gray shale to argillite; sand content in limestone increases upward such that calcareous sandstone is present near the top of the formation; limestone contains tan, wavy (irregular) silt layers and partings, and is at least locally dolomitic; mostly slope and thin ledge former; in the Brigham City quadrangle, two resistant 50- to 100-foot (15 to 30 m) thick limestone beds stand out, and a similar, thinner limestone is present at the top of the Ute (Jensen and King, 1996); this capping limestone grades irregularly upward into dolomite of the conformably overlying Blacksmith Formation, making it difficult to map this contact; base less resistant than conformably underlying upper Langston; about 690 feet (210 m) thick (Jensen and King, 1996). Maxey (1958) reported *Ehmaniella*(?) sp. and *Glossopleura* sp. trilobite fossils in and at the base of the Ute Formation, respectively, in the Wellsville Mountains, making it Middle Cambrian. See also Deputy (1984) for additional non-fossil information on the Ute in the Wellsville Mountains.

Cl **Langston Formation** – Upper part is gray, sandy dolomite and limestone; weathers to light-brown ledges and cliffs; about 240 feet (75 m) thick. Middle part is yellowish- to reddish-brown- and gray-weathering, silty, greenish-gray, fossiliferous shale, and lesser interbedded, silty, gray, laminated to very thin bedded limestone (Spence Shale Member); about 190 feet (60 m) thick. Lower part is brown-weathering, ledge-forming, gray limestone and dolomite (*Ptarmigania* strata of Resser, 1939b) and, locally, some poorly indurated sandstone (Naomi Peak Member); conformably overlies the Geertsen Canyon Quartzite; about 20 feet (6 m) thick (after Buterbaugh, 1982; Jensen and King, 1996; see also Maxey, 1958). See Buterbaugh (1982) for additional information on the lithology and depositional environments of the Langston in the Wellsville Mountains. In the Brigham City area, the Langston fossil fauna (*Glossopleura* trilobite zone in Spence Shale, *Albertella* trilobite zone in Naomi Peak) is earliest Middle Cambrian in age (Maxey, 1958; Jensen and King, 1996, table 2). The Spence Shale Member in the Wellsville Mountains contains an abundant and diverse fossil fauna that has been studied by numerous paleontologists (for example, Resser, 1939a; Gunther and Gunther, 1981; Babcock and Robison, 1988; Conway-Morris and Robison, 1988; Rigby and others, 1997; Sumrall and Sprinkle, 1999; Sprinkle and Collins, 2006; Briggs and others, 2008).

Geertsen Canyon Quartzite – These strata were previously called the Brigham Formation/Quartzite (Walcott, 1908; Eardley and Hatch, 1940) and were referred to as the Pioche(?) Formation and Prospect Mountain Quartzite by Maxey (1958). However, the exact locations of the Brigham Formation/Quartzite type locality and measured sections in the Wellsville Mountains are not known (see Walcott, 1908; Eardley and Hatch, 1940), so these incompletely described and vaguely located sections were replaced with type sections near Huntsville, Utah (Crittenden and others, 1971; Sorensen and Crittenden, 1976b), when the Brigham was elevated to group status and the Geertsen Canyon replaced most of the Brigham Quartzite. Our two map units are not the same as the informal members of Crittenden and others (1971), because their reported change in grain size and feldspar content could not be mapped, and quartz-pebble conglomerates are present in most of the Geertsen Canyon; total Geertsen Canyon about 3900 feet (1190 m) thick near Brigham City (Crittenden and Sorensen, 1985; Jensen and King, 1996) and about 3900 to 4200 feet (1190–1280 m) thick to southeast near Huntsville (Crittenden and others, 1971). The age of the Geertsen Canyon is uncertain; it could be as young as Middle Cambrian (age of overlying Langston) and as old as Neoproterozoic (age of underlying Browns Hole Formation). Subdivided into two members (map units) in Mount Pisgah quadrangle.

Cgu **Upper member** – Brown-weathering, medium- to coarse-grained, medium- to thick-bedded quartzite with interbedded very fine- to fine-grained, thin-bedded quartzite beds and micaceous argillite beds about 6 inches (15 cm) thick; argillite layers at the base and partings higher in the unit; moderately resistant overall, but less resistant than underlying lower member; contains ripple marks in argillite, cross-bedding in quartzite, as well as *Skolithos* (vertical burrows), horizontal worm burrows, and other trace fossils; weathered quartzite outcrops darker than fresh surfaces; about 360 feet (110 m) thick. Likely correlative with *Skolithos*-bearing interval 375 feet (114 m) thick that Crittenden and others (1971) noted and reported as containing abundant fucoidal structures in argillites and some trilobite tracks.

Cgl **Lower member** – Light-colored (pale-buff to white or pale-pink, with local pale-red or pale-purple streaks), medium- to coarse-grained, medium- to very thick bedded quartzite; weathers to grayish-orange-pink to pale-reddish-orange, and medium-dark-gray, blocky cliffs that are darker than fresh surfaces; contains cross-bedding, pebble layers and lenses from one pebble to 1 foot (0.3 m) thick, and some purple shaly (phyllitic) partings; pebbles are mostly rounded light-colored quartzite with some coarse (vein?) quartz; at least 3500 feet (1067 m) thick (Jensen and King, 1996), base of member is covered by Quaternary deposits north of Flat Bottom Canyon and is shown by Sorensen and Crittenden (1976a) as being in fault contact with Caddy Canyon Quartzite south of Flat Bottom Canyon. Because a bed like the volcanic part of the Browns Hole Formation is locally visible south of Flat Bottom Canyon, this fault may be a normal contact between the Mutual and Caddy Canyon Formations, with Inkom missing due to "pinch out." Lower member reportedly feldspathic (20% feldspar) in Mantua quadrangle (Crittenden and Sorensen, 1985) with unique feldspar-rich base described by Sorensen and Crittenden (1976b) and similar coarse-grained, 300- to 400-foot (90 to 120 m) thick, basal "arkose" to southeast near Huntsville (see Crittenden and others, 1971).

Precambrian (Upper Proterozoic)

Zbv **Browns Hole Formation** – We only mapped the metavolcanic (red) part of the unit (Zbv) in the Mount Pisgah quadrangle, located on ridge west of Mantua city and abutting the Mantua quadrangle; the upper quartzite reported by Sorensen and Crittenden (1976a,b) and Crittenden and Sorensen (1985) is not recognizable. Any quartzite above the metavolcanic unit looks like the Geertsen Canyon Quartzite. The metavolcanic unit is also tentatively mapped (Zbv?) to the northwest, south of Flat Bottom Canyon, where a thin, poorly resistant, reddish bed that is locally visible overlies thick dark-colored quartzite (Mutual?) and underlies a thick lighter-colored quartzite (Geertsen Canyon?).

In the Brigham City area, the upper quartzite is reportedly a white to terra-cotta (reddish orange) colored, well-sorted, medium- to fine-grained, medium-bedded, vitreous quartzite about 350 feet (105 m) thick, with the underlying metavolcanic part of the formation missing (after Sorensen and Crittenden, 1976b); quartzite described as white to pale-gray and about 115 to 270 feet (35 to 85 m) thick to the south in the Mantua quadrangle (Crittenden and Sorensen, 1985). Entire Brown Hole Formation is shown as faulted out by Box Elder "thrust" in Mount Pisgah map area by Sorensen and Crittenden (1976b). The local terra cotta coloring may be "staining" from underlying metavolcanic rocks or along fault zones.

Regionally, the Browns Hole is distinctive iron-stained to hematitic, recessive-weathering, typically vegetated, metavolcanic rocks with overlying quartzite that is at least locally distinct from the overlying Geertsen Canyon Quartzite, because it is white to pale gray, almost vitreous, and more resistant, and is not feldspathic or conglomeratic; metavolcanic rocks include basaltic to andesitic to trachytic lava flows, fragmental volcanic rocks, and volcanic-clast/fragment/grain sedimentary rocks, as well as argillite and fine-grained quartzite; mostly hematitic sandstone and siltstone to south of Browns Hole type area near South Fork Ogden River; reportedly absent to 150 feet (0–45 m) thick in Mantua quadrangle (Crittenden and Sorensen, 1985), but volcanic unit (and Mutual Formation) are present and volcanic unit is at least 150 feet (45 m) thick near North Fork of Ogden River where Crittenden and Sorensen (1985) show an excessively thick Geertsen Canyon section with no Mutual or volcanic unit; hornblende K-Ar isotopically dated at 570 ± 7 Ma (580 Ma corrected) from a trachyte cobble in this member in Huntsville quadrangle (Crittenden and Wallace, 1973; Sorensen and Crittenden, 1979). The absence of the quartzite unit implies the Geertsen Canyon Quartzite at least locally unconformably overlies the Browns Hole Formation.

Zm? **Mutual Formation** – Mapped on ridge southwest of Mantua based on overlying red bed (Browns Hole) on same ridge; queried because unit previously shown and described as faulted out by Box Elder "thrust" in area (Sorensen and Crittenden, 1976a,b; Crittenden and Sorensen, 1985). Identification also problematic because the Mutual at least locally looks lighter and grayish like Geertsen Canyon Quartzite, is as thin as about 400 feet (120 m) in the Browns Hole area (Crittenden, 1972), and may not be present to east on leading edge of Willard thrust (Coogan, 2006); so absence in Mount Pisgah and Mantua quadrangles may be due to thinning and mapping as Geertsen Canyon. As noted under unit Zbv, Sorensen and Crittenden (1976a) may have mapped the darker Mutual as Geertsen Canyon Quartzite in fault contact with the Caddy Canyon Formation.

In Mantua quadrangle, Mutual is quartzite with pebble conglomerate and argillite lenses that is locally feldspathic and commonly cross-bedded (after Sorensen and Crittenden, 1976a,b); typically weathers to distinct dark shades of purple and grayish red, and less commonly to green or brown; reportedly 2200 to 2600 feet (670 to 790 m) thick in Mantua quadrangle (Sorensen and Crittenden, 1976a,b; Crittenden and Sorensen, 1985) and our unit Zm? appears about half as thick in the Mount Pisgah quadrangle.

Zi? **Inkom Formation** – Tentatively mapped as non-resistant darker zone along Box Elder "thrust" trace; but, our Zi? unit could be wide fault zone and Inkom is shown as faulted out by Box Elder "thrust" in area (Sorensen and Crittenden, 1976a,b; Crittenden and Sorensen, 1985). Also not present and likely "pinching out" on leading edge of Willard thrust (Coogan, 2006), so absence near Brigham City might be stratigraphic rather than structural.

Regionally, Inkom is distinctive slope-forming gray to reddish-gray weathering, micaceous psammite, argillite, and meta-tuff; near Brigham City in the Mantua quadrangle, Inkom includes a lower, laminated, olive-gray to light-green, green-weathering meta-siltstone (argillite), with lenses of silver- to gray-weathering, black meta-tuff, and an upper, dark-green, grayish-red-weathering, very fine grained meta-sandstone (psammite); reportedly 20 to 200 feet (6–60 m) thick (after Sorensen and Crittenden, 1976a,b; Crittenden and Sorensen, 1985), with complete exposures southeast of Brigham City about 150 feet (45 m) thick (after Sorensen and Crittenden, 1976b) and 200 to 300 feet (60–90 m) thick in the Mantua quadrangle.

Zcc **Caddy Canyon Quartzite** – In exposures near Brigham City, mostly vitreous, almost white-weathering, variegated (tan, green, blue-green or purple, and locally light gray to white and pink), cliff-forming quartzite about 1000 to 1650 feet (300–500 m) thick (Sorensen and Crittenden, 1976a,b; Crittenden and Sorensen, 1985); typically much lighter weathering than Geertsen and Mutual Formations. Upper bed is bench of hematite-stained, brecciated quartzite (Inkom psammite?) that is at a low angle to bedding and moderately dipping; this bed is part of the Box Elder thrust fault zone of Sorensen and Crittenden, (1976a,b), with younger rocks "placed" on older rocks, a sense of offset that is opposite that of a thrust fault. Caddy Canyon reportedly conformably overlies and grades into the argillitic Papoose Creek Formation in the area (Sorensen and Crittenden, 1976b; Crittenden and Sorensen, 1985), but contact is marked by sharp change to darker weathered colors and thin bedding in, and less resistance to the Papoose Creek (see also Jensen and King, 1996).

Zpc **Papoose Creek Formation** – Argillite to psammite (meta-siltstone interbedded with quartzose meta-sandstone); interbedded brownish-weathering, light-gray and greenish-gray quartzite and darker-colored argillite or meta-siltstone with micaceous bedding surfaces; bedding is typically very thin (0.5–2 inch [1–5 cm]), largely defined by argillite, and varies from laminated to medium bedded (about 0.2–18 inches [0.5–45 cm]); near Brigham City, reportedly gray, brown, and greenish-brown siltstone with interbedded, similarly colored, fine-grained, quartzitic sandstone and some medium- to fine-grained quartzite (Sorensen and Crittenden, 1976b; Crittenden and Sorensen, 1985); also apparent relict mud cracks filled with quartzite (Jensen and King, 1996); medium-bedded, medium- to coarse-grained quartzite north of Perry Canyon in Mantua quadrangle (Crittenden and Sorensen, 1985); about 1000 feet (300 m) exposed in Mount Pisgah quadrangle, and reportedly 750 to 1500 feet (225–455 m) thick in area (Sorensen and Crittenden, 1976a,b), but appears to be no more than 1000 feet (300 m) thick in Mantua quadrangle; base gradational into underlying Kelley Canyon Formation (Sorensen, and Crittenden, 1976b) such that they did not map this contact at a consistent horizon in the Mantua quadrangle; lateral relations reportedly uncertain (Crittenden and others, 1971) but they report and show the Papoose Creek as a transitional zone between the Kelley Canyon and Caddy Canyon Formations (see Crittenden and others, 1971, in particular figure 7; Crittenden, 1972).

Zkc **Kelley Canyon Formation (may not be exposed)** – Distinctive dark-gray to black, gray- to olive-gray-weathering argillite to phyllite; upper part grades into Papoose Creek Formation such that Zpc-Zkc contact on border of map may not be in Mount Pisgah quadrangle; better exposed just south of map area in Box Elder Canyon; reportedly only 600 feet (180 m) thick in Mantua quadrangle (Sorensen and Crittenden, 1976a; Crittenden and Sorensen, 1985), but appears to be about 1000 feet (300 m) thick in Mantua quadrangle; silvery gray weathering reportedly characteristic (Sorensen and Crittenden, 1976b).

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